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Adaptations to Running While Footwear Cushioning and Surface are Manipulated

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ADAPTATIONS TO RUNNING WHILE FOOTWEAR CUSHIONING AND SURFACE ARE MANIPULATED

A Dissertation Presented

by

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DEDICATION

To my beautiful and patient wife for keeping our lives together during this process, and to my parents for support and encouragement throughout.

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ABSTRACT

ADAPTATIONS TO RUNNING WHILE FOOTWEAR CUSHIONING AND SURFACE ARE MANIPULATED

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Minimal footwear sales have encountered rapid growth over the last several years. Minimal footwear are often constructed with thin basic uppers and thin, flexible midsoles. It is likely that running in minimal footwear will require adaptation and adjustments as the amount of cushioning and the geometry of the foot/ground interface will be substantially different than what many are accustomed to. This research investigated the effect footwear cushioning amount and the running surface had on running patterns. Study 1 (Chapter IV) utilized two different running footwear conditions and two different cushioned treadmill conditions, as well as a barefoot condition, to investigate the effect cushioning magnitude and mode had on running patterns. Subjects ran for six minutes at 3.0 m/s for each footwear/surface condition while kinematics and acceleration data were collected. Study 2 (Chapter V) utilized three footwear conditions as well as a barefoot condition to investigate the effect of running in minimal footwear for the first time. Subjects ran for six minutes at 3.0 m/s while wearing each of the four conditions on an aluminum belt treadmill while kinematic and acceleration data were collected. The three footwear conditions were very similar except for the amount of underfoot material (foam) which varied from very little in the most

minimal condition to a typical training footwear amount in the thickest condition. Study 3 (Chapter VI) utilized the same three footwear conditions worn in study 2. Subjects ran for 30 minutes at 3.0 m/s wearing each of the three footwear conditions while kinematic and acceleration data were collected in order to investigate the response to minimal footwear over the course of a sustained run. Results of Study 1 suggest that the amount of underfoot cushioning as well as how that cushioning was applied (footwear vs. surface) were both important and affected adjustments made during the run. The foot was more horizontal, the ankle joint complex more plantar flexed, and the knee more flexed in the sagittal plane at TD when running barefoot compared to all other conditions. Peak acceleration values were reduced for the most cushioned condition compared to all others. The thigh segment was more vertical at TD and peak tibial internal rotation at midstance was reduced when footwear were worn. This indicated cushioning provided through footwear altered running patterns compared to cushioning provided through the surface. More investigation is necessary to fully understand all the factors involved, but our research showed that cushioning magnitude is not the only factor affecting running patterns when footwear or running surface is altered. Some Study 2 dependent variables indicated running patterns to be significantly different for both barefoot and very minimal footwear conditions compared to footwear with thicknesses more similar to typical training footwear. Other dependent variables showed barefoot to separate from all footwear conditions implying that unique strategies were utilized for barefoot running even when compared to minimal footwear providing very little cushioning or protection. Peak accelerations implied that cushioning limited the shock transferred to the tibia and the head. Most coordination measures implied barefoot running to be significantly more variable than running in minimal running shoes. Adaptations due to running in footwear with unknown cushioning characteristics occurred quickly, in as few as six to eight steps. Kinematic adjustments were also occurring later in the six minute run. Study 3 kinematic and acceleration dependent variables indicated adjustments were made to running patterns as a result of changes in the amount of underfoot material. The foot segment was less horizontal and the AJC more dorsiflexed for the thick condition compared to both others. These changes did not completely compensate for changes in underfoot material however, as peak accelerations at the tibia and the head were increased as underfoot material was reduced. Runners were found to adjust running patterns as the thirty minute run progressed regardless of footwear condition. Several kinematic dependent variables were found to significantly increase or decrease as the 30 minute run progressed. In summary, the amount of cushioning and the mode of cushioning were found to effect running patterns. Given these findings, it is not surprising adaptations were found when comparing running in minimal footwear to running in footwear with more typical midsole thicknesses. Cushioning magnitude and the geometry of the foot/ground interface were substantially different between these footwear conditions. Although the thin condition provided almost no cushioning, differences were still shown between barefoot and this condition. Barefoot running may require a unique solution even compared to running in extremely minimal footwear. When runners wore minimal running shoes for the first time, some adaptations occurred quickly; however, adjustments were still occurring much later into the six and 30 minute runs. Runners who purchase minimal footwear can expect changes in running patterns.

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CHAPTER I

DEVELOPMENT OF THE PROBLEM

Introduction

Injuries have plagued runners since the running boom occurred in the late 1970's. Although much research has focused on running and running related injuries, the number of runners who get injured has not been reduced (Clement & Taunton, 1981; Taunton, et al., 2002) There are at least two explanations for this; either we as scientists are not asking the correct questions, or our answers are not being implemented correctly. One thing that is common to nearly all runners is shoes.

Problem or Solution

Running footwear has been and continues to be implicated as a risk factor or a solution to running related injuries. There are some who believe modern running footwear to be the problem. Robbins and Waked (1997b) found pre-existing beliefs like those in common advertising to be potentially detrimental. Authors believe this explains the 123% higher injury frequency found when wearing more expensive footwear compared with cheap alternatives (Robbins & Waked). These authors also believe thick ethlylene-vinyl acetate (EVA) in modern running footwear necessitates a large impact force in an attempt to transform the interface into a more stable surface (Robbins & Waked, 1997a). Balance has also been shown to suffer with thick soft shoes (Robbins, Waked, Allard, McClaran, & Krouglicof, 1997). On the other hand, there are many who would argue that running footwear can be part of the solution to injury. Denoth (1986) used dynamic estimations to show a more compliant midsole to reduce ligamentous forces and increases joint forces. Depending on the injury history of a runner, this may be a benefit. Divert et al. (2005) suggested that the purpose of the shoe is to "protect the foot and leg structure by means of a damping and low stiffness material." Much research has taken place on the beneficial aspects of footwear. Milgrom et al. (1992) found basketball shoes to be superior to normal military boots in reducing the number of stress fractures and other injuries of the foot. Rome et al. (2005) concluded in a review that the use of shock absorbing insoles in footwear will probably reduce the occurrence of stress fractures in military personnel. Hunter et al. (2007) state that patella misalignment is potentially modifiable through footwear. Cornwall and McPoil (1995) found footwear to reduce maximal tibial internal rotation, which is thought by some to be related to knee injuries. Similarly, Butler et al., (2006) found motion control footwear to limit rearfoot motion better than neutral cushioning footwear.

Running Injuries

Running injuries can be divided into two categories; traumatic injuries and overuse or cumulative micro-trauma injuries. Traumatic or acute injuries can be defined as those caused by a single, traumatic event (macro-trauma) (Matava, 2008). Traumatic injuries have received some attention in the literature and would include; ankle sprains, cut/scrapes, etc. Overuse injuries are much more subtle and normally occur over time. These injuries are a result of repetitive micro-trauma and stress which normally results in inflammation (Hertling & Kessler, 1996; Matava). Overuse injuries have received a great deal of attention in the biomechanics literature on topics related to "over" pronation, Iliotibial Band Syndrome, Patellofemoral Syndrome, Achilles Tendonitis, stress fractures, etc. (Cheung, Ng, & Chen, 2006; Clancy, Neidhart, & Brand, 1976; Gillespie & Grant, 2000; R. H. Miller, Meardon, Derrick, & Gillette, 2008; Taunton, et al., 2002; Tiberio, 1987)

Traumatic Injuries

Where traumatic injuries are concerned, footwear can also be thought of as the possible problem or potential solution. Research on midsole thickness in cutting maneuvers has suggested a thick midsole can result in more inversion at the ankle during cutting tasks (TenBroek, Umberger, & Hinrichs, 2006). If a thick midsole produces too much inversion, it could be a contributing factor in traumatic ankle sprain. Alternately, if a midsole is relatively thin, it may help those with chronic ankle instability reduce the number of traumatic sprains they incur. On the other extreme, some athletes choose to run barefoot for a variety of reasons. Running barefoot leaves the plantar surface of the foot vulnerable to a number of potentially cut/scrape producing obstacles including rocks and sticks. These traumatic injuries, although often not serious, can be troubling and a shoe would protect these athletes from some environmental dangers of a trail or sidewalk.

Cumulative Micro-trauma or Overuse Injuries

Overuse injuries relate to a tissue being stressed repeatedly, leading to some breakdown of that tissue (i.e. an injury). For example, stress fractures result from fatigue failure in a bone. Stress fractures in the tibia are a common injury to athletes, especially runners. These fractures can be simple microfractures causing the rupture of bony cortices and a fracture line (Hertling & Kessler, 1996). Another common running injury is iliotibial band syndrome (ITBS) in which there is inflammation in the iliotibial band (ITB) possibly because of impingement (Fredericson & Wolf, 2005), lateral compression (Fairclough, et al., 2006; R. H. Miller, et al., 2008), or large strain rates (Hamill, Miller, Noehren, & Davis, 2008). Many runners also obtain some form of patella femoral pain syndrome which is thought to be caused by increases in tibial torsion, Q angle and pronation (Norkin & Levangie, 1992). Countless studies have been done to determine the reason for these injuries and on how to prevent them and others like them. Where footwear fits into injuries with predispositions and causes as complex as these is unclear. Robbins and Waked (1997a) state that for an injury like tibial stress fractures, modern cushioned footwear mask the magnitude of shock being transferred up the kinematic chain. Conversely, physicians and podiatrists often prescribe a soft athletic footwear to those who have a history of stress fractures, and soft insoles have been shown to reduce the incidence of stress fractures (Gillespie & Grant, 2000).

Potential Compromise

The ideal situation would be footwear which is not related to the cause of overuse injuries or traumatic injuries. Some have claimed modern running footwear to be potentially over cushioned (Robbins & Waked, 1997a; Robbins, et al., 1997). Those who run barefoot may agree. Others believe running barefoot allows the athlete to run "naturally", or "as nature intended"; potentially taking advantage of the body's "natural" shock attenuation and energy return capabilities. For example, tendons are about 88-95% efficient whereas footwear midsole materials are around 60-70% efficient (R. Alexander & Bennet, 1989; Bennet, Ker, Dimery, & Alexander, 1986; Shorten, 1993; D. J. Stefanyshyn & Nigg, 2000a). Staheli (1991) references numerous articles studying predominantly barefoot people all showing very healthy feet (Engle & Morton, 1931; Hoffman, 1905; James; Sim-Fook & Hodgson, 1958). It is possible that what is considered normal in foot morphology and range of motion has changed since these papers were written, but these findings still show relatively healthy feet when barefoot. Staheli (1991) states: “the shoe should in no other way influence the normal foot than to protect it against lesion and coldness.” Protecting the plantar surface of the foot is likely even more important today than it was when the research was conducted Staheli references. In contrast, Divert et al. (2005a) inferred the purpose of the shoe was to “protect the foot and leg structure by means of a damping and low stiffness material.” The former definition would support minimalistic running footwear and the latter traditional training footwear.

Minimal Footwear

Minimal footwear is defined by the footwear industry as a shoe with a thin, flexible midsole and outsole and a light, basic upper with little or no heel counter. Our focus will be the thickness and cushioning of the midsole. If Robbin’s theory about the midsole masking the magnitude of impact shock is correct, this thinner midsole may allow runners to sense the severity of impacts and adjust kinematics accordingly. This behavior has been shown previously. A classic study by Clarke et al. (1983) using footwear with different midsole hardnesses found subjects adjusted running kinematics in such a way that impact forces were not grossly different, a finding others have since replicated (Hennig, Valiant, & Liu, 1996). In addition, if a runner is touching down on the lateral edge of the rear of the shoe, which many do (B. Nigg, 1986), a thinner midsole may reduce the lever arm between the ground reaction force and the ankle complex. This may reduce the amount of pronation and possibly reduce pronation velocity (B. Nigg). “Over” pronation although difficult to define, has been implicated in overuse injuries (Clement & Taunton, 1981).

Reducing midsole thickness may result in kinematic changes. Overuse injuries are likely caused by a tissue being stressed repeatedly due to some cyclic activity, i.e. running. A repeated movement taxes tissues and may increase the risk of injuring the weakest tissues. Running in minimal footwear may stress stronger tissues, or shift injuries to previously healthy tissues. Milgrom et al. (1992) showed modified basketball shoes to reduce the number of foot related injuries in military recruits; however, the total number of injuries did not change. Minimal footwear has potential benefits in terms of overuse injuries; however, as Milgrom et al found, it may simply shift injury location instead of actually reducing overall injury numbers.

Minimal footwear may also help mitigate traumatic injuries. Going from typical training footwear to minimal footwear will likely mean a reduction in midsole thickness. It has been shown that a reduction in midsole thickness can reduce the inversion angle of the ankle during cutting maneuvers (TenBroek, et al., 2006). This reduction in inversion angle could mean a decrease in the number or severity of the lateral ankle sprains that are so prevalent among athletes (DiGiovanni, Partal, & Baumhauer, 2004). A reduction in midsole thickness could also improve balance. Robbins et al. (1997) used a balance beam and 17 subjects with a mean age of 33 yrs to show that a thin, hard midsole leads to improved balance. Improved balance could lead to reductions in traumatic injuries among runners although it is unclear how a small improvement in balance would affect injury. Also, compared to barefoot running, any level of protection of the plantar surface of the foot should reduce the number of cuts and scrapes the feet suffer.

Research on Minimal Footwear

Research on how runners will react to such minimal footwear is sparse. Fong et al. (2007) compared a "minimal" cloth upper shoe constructed to be inexpensive for the consumer. These shoes had a thin, flexible sole compared to traditional running footwear. These footwear are/were used extensively by school age children in Hong Kong mainly due to their cost effectiveness. Their protective nature was questioned by scientists and educators, prompting a biomechanical study. This study used a human pendulum device to measure differences in impact force on a vertically mounted forceplate. Subjects (mean age 12.7) were forced into a locked knee, heel first contact with the forceplate. Results showed minimal footwear produced larger impact forces compared to traditional running footwear but were not different than barefoot (Fong, et al., 2007). A limitation of this study is the lack of kinematic changes athletes can and probably would make when impact forces become high. These adaptations would be important for athletes utilizing minimal footwear. Without kinematic adjustments, these findings are little more than a basic impact test similar to the test done by Clark et al (1983) showing comparable results.

Research has been done on the Nike Free (Nike Inc., Beaverton, OR) which can be considered a minimal shoe compared to traditional training footwear. This footwear has a simple thin upper, no heel counter, and deep flexibility grooves running in the antero-posterior (AP) direction as well as the medio-lateral (ML) direction. Potthast et al. (2005, unpublished) showed similar range of motion and plantar pressures using minimal footwear and walking barefoot on grass. In other pilot work, these authors found activity of the flexor hallicus longus to be elevated in the minimal footwear compared to traditional training footwear during walking and slow running. Potthast and colleagues also performed a study in which some athletes performed a warm up using the Nike Free before each work out while the control group performed all exercises in their traditional training footwear. The experimental group showed increased strength and cross sectional area in select lower extremity intrinsic and extrinsic foot muscles (Potthast, et al., 2005). Although providing useful information, these studies provide little in terms of kinematic adjustments while running in minimal footwear.

Hamill et al. (1988) compared a traditional training shoe and a racing flat while recreationally active females ran at a speed corresponding to 90% of their VO_2 max as predetermined during a progressive speed, peak oxygen uptake treadmill test. Subjects were required to run at this speed for 15 minutes in each shoe on separate days. Although this protocol likely was difficult for subjects and resulted in some measure of fatigue, rearfoot motion was unchanged throughout the run. The differences in rearfoot motion were striking. The racing flat showed a 42% greater maximum eversion than the traditional training footwear. Cavanagh stated footwear with firmer midsoles, wider heel bases, and stiffer heel counters should control pronation relatively better (Cavanagh, 1981). Hamill stated the racing shoe was less firm, had a softer heel counter, and was narrower with some material cutout on the bottom of the shoe in the arch region. Also, although not statistically significant, the lighter racing flat resulted in a 1.3% lower VO_2 (Hamill, et al., 1988). Rearfoot motion and mass effects will be further addressed in the Barefoot vs. Shod section of Chapter 2.

Squadrone and Gallozzi (2009) used an instrumented treadmill and experienced barefoot runners to investigate a particular minimal shoe. Subjects were given a pair of

Vibram Fivefingers (Vibram USA, Concord, MA) and a pair of typical training footwear (TTF) ten days before their data collection to become accustomed to the footwear conditions. Subjects ran in six minute bouts barefoot, with the Vibram Fivefingers, and in TTF. Running patterns in the Fivefingers resembled barefoot running more than the TTF condition, but spatio-temporal variables were more similar to the TTF condition. The foot was found to be significantly more plantar flexed at TD when barefoot or wearing the Fivefingers compared to the TTF. This translated to a flatter foot placement at contact for the barefoot or Fivefingers conditions. Impact forces were also reduced with the Fivefingers shoe partially as a result of kinematic alterations made to shorten stride length and increase stride frequency. Contact times between the barefoot and Fivefingers were similar but flight times were greater for the Fivefingers. Authors speculate the differences in flight times between Fivefingers and barefoot might result from the protection the Fivefingers does provide compared to barefoot, which may be enough to accomplish a more vigorous push off.

Barefoot Running

One may infer that as footwear becomes more minimal, runners would migrate towards running kinematics utilized by those who chose to run barefoot. Many have shown that runners' kinematics are different barefoot than they are shod (De Wit, De Clercq, & Aerts, 2000; Divert, et al., 2005a; Divert, Mornieux, Baur, Mayer, & Belli, 2005b). Exactly why this is the case is not so clear. How the kinematics of a runner will change due to minimal footwear may be related to why runners chose, consciously or subconsciously, to run differently when barefoot.

Runners may adjust kinematics when barefoot to effectively run more "cautiously" due to the lack of protection of the plantar surface of the foot. While running barefoot, the plantar surface of the foot would be very susceptible to any sharp objects on the track or trail. If the change in kinematics is solely due to this issue, running in minimal footwear may produce similar kinematics to running in TTF because the plantar surface would be protected from cuts and scrapes. This may not be the only issue while running barefoot.

In TTF the outsole and midsole (typically EVA) would reduce high pressures at the plantar surface of the foot while running. Barefoot, no such reductions would take place. An obstacle does not have to pierce the skin to be painful. An object creating high pressures during stance could be very painful as the plantar surface of the foot is very sensitive. Depending on how minimal a shoe is, pressure could vary significantly. Thus, TTF may not only protect from cuts and scrapes but also high pressures.

Changes in running patterns when barefoot and shod could simply be a result of the loss of cushioning/shock absorption typically provided by the midsole. Those who believe footwear should attenuate impact loading would likely agree. The heel fat pad has been shown to compress substantially at heel strike when barefoot (over 60% barefoot compared to 36% shod), which may reduce the limited shock absorption of which it is capable (Bruggemann & Arndt, 1994). Without the midsole to absorb shock and the heel pad compressed substantially, large shock waves may travel up the kinematic chain. This may require kinematic adjustments when compared to running in TTF. Running with a traditional heel toe strike pattern may be possible when the midsole can attenuate shock, but when barefoot, the heel fat pad may not provide enough shock attenuation and kinematics may be adjusted. The level of compensation required when wearing minimal footwear may be a product of the shoe *and* the runner. Each runner/athlete would have individual fat pad characteristics, overall body mass, and running mechanics, all of which contribute to impact forces and shock attenuation (B. Nigg, 1986). How footwear affects shock will likely be a result of its midsole material and thickness. Thus, the level of kinematic adjustment due to loss of cushioning in a minimal shoe may be a result of how much shock absorption capability exists in the footwear and the individual athlete.

Changes in kinematics could also occur because of the large changes in the foot/ground geometry (De Wit, et al., 2000) when typical TTF are worn. In many TTF, the additional material between the posterior foot and the outsole is approximately 3.0 cm. This material under the heel, the midfoot, the metatarsals, and toes could alter footstrike mechanics. In addition, TTF also alter the geometry of the foot/ground interface by building "lift" into the midsole, meaning the heel has more thickness than does the mid and forefoot. Nigg (1986) discusses in his book "Biomechanics of Running Shoes" how adding the midsole to a barefoot creates a larger external eversion torque and a larger plantar flexion torque at touchdown. The ground reaction force and the increased moment arm create torques very different than when not wearing footwear. These differences could be enough to cause kinematic changes when barefoot running and shod running are compared.

There are several possibilities as to why we run differently when barefoot. Many studies have addressed these possibilities, but none to this researcher's knowledge have investigated directly which factors effect these kinematic changes. In addition, it is unknown how quickly these adjustments occur when wearing minimal footwear for the first time.

Significance of the Study

Those who suffer from overuse injuries while wearing traditional training footwear may benefit from a change in their running pattern. Minimal footwear may require kinematic changes resulting in injury reductions through a shift in the tissues most stressed during running. Barefoot runners are at risk for traumatic injuries due to the plantar surface of the foot being unprotected. A shoe made with a thin, flexible midsole, with a basic, light upper and no heel counter may benefit barefoot runners by protecting the plantar surface of the foot while not changing what they enjoy about barefoot running. In these cases, a minimal running shoe could benefit both groups by reducing the number of injuries incurred during running.

What is not clear is how runners who are used to running in TTF would react to wearing minimal footwear. Minimal footwear may have very different impact attenuation properties than TTF, although athletes have been shown to adjust kinematics to regulate impact characteristics with different footwear (Hennig, et al., 1996; B. M. Nigg, Denoth, Luethi, & Stacoff, 1983).

The athletes in this study will be running on a treadmill in a very controlled environment. Although the findings of these experiments may not translate directly to running outdoors in an uncontrolled environment, it is likely some inferences can be made. Gaining knowledge into when and why athletes change their kinematic pattern when footwear changes can only benefit the running community.

Assumptions

- The volunteers utilized in this study are normal runners whom train predominantly in TTF.
- The volunteers utilized in this study are not familiar with running in minimal footwear, and therefore running in a minimal shoe will be somewhat of a novel task.
- The movement patterns on a treadmill are somewhat representative of movement patterns during over ground running.

Hypotheses

Hypotheses related to study 1which aimed to determining if cushioning magnitude and cushioning mode affect how athletes run.

1. Running patterns will change when running barefoot on a cushioned surface versus running in footwear on a normal surface even though the cushioning properties of the foot/ground interface will be similar. Many running footwear provide a geometry change for the foot/ground interface through a foam midsole which is thicker in the heel than it is in the forefoot. Additionally, the foot is constrained to some degree when a shoe is worn which may affect running patterns. Finally, although cushioning is provided in both conditions, the shoe potentially offers greater protection and security since the shoes are on foot before the run begins. This may result in more confidence in the cushioning and protection provided. For these reasons we hypothesized different kinematic patterns when shoes are worn versus not worn even though the cushioning amount is similar.
2. Runners will adjust kinematic patterns when cushioning is reduced consistent with the findings of De Wit et al. (2000). These changes will include a more horizontal

foot touchdown due to greater plantar flexion and a more vertical leg at contact, more flexion of the knee at midstance, and a reduced stance time.

Hypotheses related to study 2 which aims to gather kinematic, shock attenuation, and coordination information on how runners accustomed to wearing TTF respond to running in a minimal shoe from their first step until reaching the end of a six minute run (Hardin, van den Bogert, & Hamill, 2004).

1. Runners will adjust kinematic pattern based on footwear condition. De Wit et al. (2000) found subjects reduced sagital foot segment angle at touchdown, increased plantar flexion angle at touchdown, and adjusted the leg segment angle at touchdown to be more vertical when going from shod to barefoot. The same is hypothesized to occur here with minimal footwear resulting in kinematics somewhere between barefoot and footwear with midsole thicknesses more like traditional training footwear.
2. As footwear conditions become more minimal, tibial acceleration and shock attenuation as will be increased Unold (1974) found barefoot running to have the largest tibial acceleration compared to shod conditions, and the shod condition most closely resembling modern training footwear to have the least tibial accelerations.
3. Runners will show greater coordination variability as measured by continuous relative phase couplings at all time points when wearing minimal footwear during a run. The minimal footwear conditions will be enough of a novel task to increase coordination variability over the entire six minute run compared to thicker footwear.
4. Runners will adjust kinematic patterns as a result of footwear conditions quickly during the treadmill run, but not in one step. Ferris et al. (1999) found runners

adjusted leg stiffness very accurately and quickly as they ran from a consistent surface on the runway over a forceplate with a different surface stiffness. Runners made adjustments within a single step onto the new surface with sufficient practice. It is unclear how runners will respond to running in something minimal for the first time. For many, running in something minimal may be a novel task which requires exploration and learning. These individuals might require several steps in order to discover a suitable kinematic pattern.

Hypotheses related to study 3 which aim to gather kinematic and shock attenuation information on how runners accustomed to wearing TTF respond to running in a minimal shoe for an extended run lasting 30 minutes.

1. Runners will adjust kinematic pattern based on footwear condition. De Wit et al. (2000) found subjects reduced sagital foot segment angle at touchdown, increased plantar flexion angle at touchdown, and adjusted the leg segment angle at touchdown to be more vertical when going from shod to barefoot. The same is hypothesized to occur here with minimal footwear resulting in kinematics similar to the barefoot responses in De Wit et al. compared to footwear with midsole thicknesses more like traditional training footwear.
2. As footwear conditions become more minimal, tibial acceleration and shock attenuation as will be increased Unold (1974) found barefoot running to have the largest tibial acceleration compared to shod conditions, and the shod condition most closely resembling modern training footwear to have the least tibial accelerations.
3. Individuals accustomed to running in TTF will adjust their running patterns during the run in the minimal footwear condition. Willson and Kernozek (1999) found

greater forefoot loading when runners were fatigued. This change may be a result of fatigue or simply a result of consecutive impacts resulting in conscious or sub-conscious changes in kinematic and kinetic patterns. If the cumulative nature of impacts during a sustained run is causing this change, it is likely to be exacerbated when wearing a minimal shoe.

4. Over the course of a sustained run, tibial accelerations will become greater in the minimal footwear conditions. This increase in tibial accelerations will require greater shock attenuation and thus a change in the transfer function allowing accelerations at the head to remain consistent.

Summary

A large percentage of runners get injured at some point in their running careers. Some believe modern TTF to be part of the problem and others believe TTF can be helpful in preventing and treating these injuries. Those who believe modern TTF to be overbuilt may believe minimal footwear could help reduce injury rates. Those who run barefoot may benefit from the plantar protection provided by a minimal shoe. Research on minimal footwear is limited and it is unknown how athletes will respond to running in footwear with very thin midsoles for the first time. Studies 1 and 2 (Chapters V and VI) will also provide information on how quickly runners adjust when wearing minimal footwear and also investigate how the repetitive impacts of a sustained run alter running patterns.

Minimal footwear will have reduced shock attenuation properties compared to TTF. When athletes run barefoot, kinematic changes occur. Why this is the case is less definitive. Providing cushioning without footwear during a controlled treadmill run may provide additional knowledge on this topic (Study 1 – Chapter IV).

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CHAPTER II

REVIEW OF LITERATURE

Introduction

While the majority of runners run in traditional training footwear, there are some runners who train barefoot for the majority of their runs. Some individuals believe overbuilt traditional training footwear (TTF) to be a risk factor for overuse injuries and would suggest running barefoot; however, barefoot running exposes runners to traumatic injuries. A potential solution may be a minimal shoe, taking advantage of the potential benefits from both training conditions. This chapter will review some of the relevant literature to explore how runners may respond to running in these minimal footwear.

Minimal Footwear

The footwear industry defines minimal footwear as a shoe with a thin, flexible midsole and outsole with a light, basic upper with little or no heel counter. Overall the literature is very sparse regarding minimal footwear and the effects on runners. There are a few research studies utilizing what would be considered minimal footwear. One of these studies did research on a very simple shoe used widely by school aged children in Hong Kong (Fong, et al., 2007). Another group focused on the Nike Free (Nike Inc., Beaverton, OR), a production shoe from Nike (Potthast, et al., 2005). Hamill and colleagues (1988) compared TTF to a racing flat, where the racing flat was lighter and likely more flexible. Finally, Squadrone and Gallozzi (2009) compared a TTF, barefoot, and the Vibram Fivefinger (Vibram USA, Concord, MA).

Fong et al. (2007) compared a "minimal" shoe to running shoes, basketball shoes, cross training shoes, and barefoot. The minimal footwear in this study were made to be very cheap, flexible and light using cloth for the upper and a very thin sole. These footwear are used extensively by school aged children in Hong Kong. This study used a human pendulum devise to measure differences in impact force. Subjects (mean age 12.7) were forced into a locked kneed, heel contact first impact with a vertical forceplate. The velocity of contact was designed to mimic a typical touchdown velocity of a runner during a mild intensity run (3.6 m/s). Results showed minimal footwear produced greater impact forces compared to traditional running footwear, cross-training shoes, and basketball shoes but were not different than barefoot. This study does not address any kinematic changes athletes can and probably would make when impact forces become high or are expected to be high.

Also addressed in this study was lateral stability. Subjects did a sideways and forward run-up before performing a cutting maneuver on a force platform in each of the footwear conditions described previously. Results of this aspect of the study showed no significant differences between the footwear conditions. Inversion angles were less than those reported in other studies where adults performed cutting maneuvers (Stacoff, Steger, Stussi, & Reinschmidt, 1996; TenBroek, et al., 2006), which may explain finding no significant differences.

Potthast and colleagues conducted research on to the Nike Free and determined range of motion, plantar pressures, muscular activity and strength in various footwear conditions (Potthast, et al., 2005). This shoe has a simple thin upper, no heel counter, and deep flexes grooves running in the anterior-posterior direction as well as the medial-lateral direction allowing for very good flexibility. Potthast and colleagues also conducted unpublished pilot research showing similar range of motion and plantar pressures between minimal footwear and barefoot while walking on grass. In other pilot work, they found activity of the flexor hallicus longus to be elevated in the minimal footwear compared to TTF during walking and slow running. These researchers also performed a study in which the experimental group performed a warm up using the Nike Free before each work out while the control group performed all exercises in their TTF. The experimental group showed increased strength and cross sectional area in select lower extremity intrinsic and extrinsic foot muscles (Potthast, et al., 2005).

Hamill et al. (1988) compared a TTF and a racing flat while recreationally active females ran at a speed corresponding to 90% of their VO_2 max. Subjects were required to run at this speed for 15 minutes in each shoe on separate days. Although this protocol was difficult for subjects and also resulted in some measure of fatigue, rearfoot motion was unchanged throughout the run. The differences in rearfoot motion between footwear conditions were striking. The racing flat showed a 42% greater maximum rearfoot angle than the traditional training footwear. Cavanagh (1981) stated that footwear with firmer midsoles, wider heel bases, and stiffer heel counters should control pronation relatively better. The racing shoe was softer, had a less rigid heel counter, was narrower, with the arch cutout on the bottom of the shoe. Also, although not statistically significant, the weight difference may have resulted in a 1.3% lower VO_2 for the lighter racing flat (Hamill, et al.). Rearfoot motion and weight will be further addressed in the Barefoot vs. Shod section.

Squadrone and Gallozzi (2009) used an instrumented treadmill and experienced barefoot runners to investigate a particular minimal shoe. Subjects were given a pair of Vibram Fivefingers and a pair of TTF ten days before their data collection to become accustomed to the footwear conditions. Subjects ran in six minute bouts barefoot, with the Vibram Fivefingers, and in TTF. Running patterns in the Fivefingers resembled barefoot running more than the TTF condition, but spatio-temporal variables were more similar to TTF. The foot was found to be significantly more plantar flexed when barefoot or wearing the Fivefingers compared to the TTF. This also translated to a flatter foot placement at contact for the barefoot and Fivefingers conditions. Impact forces were also reduced with the Fivefingers shoe potentially as a result of kinematic alterations made to shorten stride length and increase stride frequency. Contact times between the barefoot and Fivefingers were similar but flight times were greater for the Fivefingers. Authors speculate the differences in flight times between Fivefingers and barefoot might result from the protection the Fivefingers does provide. It appeared to be enough protection to accomplish a more vigorous push off when compared to barefoot.

Some of this research is seemingly relevant to how athletes may respond to running in minimal footwear for the first time. Hamill et al's (1988) work focuses on rearfoot motion and metabolic data. Squadrone and Gallozzi's research investigated kinematics, force data, and pressure information; however, kinematic analysis was limited and subjects had ten days to become accustomed to the footwear (2009). The work of Potthast et al. (2005) is interesting but lacks the immediate response to the footwear. Research on minimal footwear is limited. The most minimal situation possible is to run barefoot. A plethora of research has taken place comparing TTF running to barefoot running and this research is worth revisiting.

Barefoot vs. Shod

Through the variety of studies comparing barefoot to shod, many areas have been addressed. The dependent variables discussed in these studies are closely related and discussing them individually is difficult; however, an attempt will be made to segregate the literature into sections. Topics to be discussed include impact forces, leg stiffness, kinematic differences, and several others.

Impact Forces

Conclusions from research comparing impact forces from barefoot running and shod running have been inconsistent (Divert, et al., 2005b). This lack of consistency is likely due to methodological issues. If subjects are forced to maintain a heel toe running style when barefoot, impact forces should increase when much like what Fong et al. (2007) found. Komi et al. (1987) also showed large impact force differences between barefoot and shod running, but only four subjects were utilized resulting in a lack of statistical power. Fong et al. reported an 1800 N peak impact force for barefoot compared to 1350 N shod. If subjects are required to run a substantial amount barefoot, they may alter their running pattern to produce a midfoot/forefoot strike pattern and reduced stride length. These adjustments are likely to affect impact forces. Studies involving a forceplate typically only require subjects to run short distances for a limited number of trials. Subjects could maintain a heel toe running pattern barefoot for this finite number of non-consecutive strides; however, this may not be relevant for runners. In more recent studies using force treadmills, which allow force measurements for many consecutive strides, subjects apparently adjusted running patterns to reduce impact forces while barefoot (Divert, et al., 2005a; Divert, et al., 2005b). One such study found this reduction to be 3.5% (Divert, et al.). Without adjustments, barefoot running should result in increased impact forces; however, subjects may adjust running patterns preventing large increases.

Loading Rate

Wright et al. (1998) define loading rate as the time derivative of the vertical ground reaction force (GRF). Biological tissues are sensitive to the rate a load is applied (Zhang, 2005). Loading rate has been shown to be greater in barefoot running compared with shod running (De Clercq, Aerts, & Kunnen, 1994; De Wit, et al., 2000). This result could be related to the reduced cushioning available without footwear. De Clercq et al. found that the heel fat pad compresses over 60% when running barefoot compared to 36% when shod. Given the seemingly less compliant system when barefoot, the loading rate increase is not unexpected.

Tibial Acceleration

A tibial mounted single axis accelerometer measures the time rate of change of velocity of the tibia (Cunningham, 1976). These accelerations can provide information which is related to impact forces and thus can provide insight into impact variables. Often in running research, the accelerometer is firmly attached to the inferior, antero-medial leg on the tibia using tape or an elastic strap. One benefit to using an accelerometer is that subjects are not required to target a forceplate. Subjects are able to run in a more natural environment such as around a track or on a treadmill when an accelerometer is utilized.

Many researchers have used accelerometers in an attempt to investigate GRF. Unold (1974) used accelerometers while subjects ran with three footwear conditions and barefoot at 4 m/s with a fixed stride frequency. Tibial accelerations were greatest when barefoot, and TTF resulted in the least acceleration. Using acceleration and mass, Newton's second law (F=m*a) can be exploited to estimate force. The limitation of this technique relates to the interpretation. Given the heavy involvement of the hip, knee, and ankle in at touchdown in running, the mass affected by impact can change. Bobbert et al. (1992) found the first peak in GRF to be related to the lower leg not rotating about the knee (knee flexion) as the thigh rotates about the hip (hip flexion) at contact. The ability of knee (and other joints) to effect the GRF has been termed effective mass, which can be defined as the portion of the mass that is accelerated (Derrick, Dereu, & McLean, 2002).

Effective Mass

Without considering effective mass or Bobbert et al.'s (1992) findings, a large tibial acceleration value would imply a large GRF. When effective mass is considered, this may not be the case. Denoth (1986) used a three-link system and experimental data to explore initial knee angle and effective mass in many activities. Denoth stated that knee contact angle seems to have the greatest influence on effective mass at about 160-170 degrees. As the knee becomes more extended, the effective mass increases. The ankle has also been shown to influence effective mass. Valiant (1990) suggested that as the rearfoot angle increases, effective mass would tend to decrease. Derrick et al. (2002) found increasing rearfoot angle at TD with fatigue, likely leading to decreased effective mass. A smaller effective mass would be easier to accelerate and greater peak accelerations would be measured. Thus, greater peak accelerations may be expected given a more flexed knee and a greater inversion angle at contact. This will not necessarily increase injury possibilities. A smaller effective mass may cause greater peak accelerations and smaller impact forces. An example of this is shown in Derrick et al. using a spring-damper model. This model showed reduced effective mass to decrease impact peak and increase peak acceleration. This could also be the reason Unold (1974) showed elevated tibial accelerations for the barefoot condition.

Leg Stiffness

Another dependent variable directly related to the effective mass discussion is leg stiffness. As the knee angle and inversion angle are manipulated, leg stiffness is affected. Overall, research has shown little variation in leg stiffness across species and speeds (Farley, Glasheen, & McMahon, 1993; He, Kram, & McMahon, 1991); however, Divert et al. (2005a) found leg stiffness to be greater for barefoot running when compared to shod running in humans. Leg stiffness was estimated by dividing force by the change in leg length ($k = F/\Delta L$). F was the peak vertical GRF and ΔL was calculated using the double integral of peak vertical acceleration. Vertical displacement and leg compression were also both higher for shod running (0.06 m to 0.07 m – vertical displacement, 0.18 m to 0.19 m – leg compression). Divert et al. attributed the changes in stiffness values to the footwear being in series with the musculoskeletal system. If the subject maintained similar musculoskeletal activation dynamics, and the footwear is in series, this will result in more compliance compared to barefoot running. Activation dynamics were not the same between shod and barefoot possibly implying an active change in leg stiffness as a result of footwear conditions.

Kerdok and colleagues utilized experimental platforms with variable stiffness fit onto a force treadmill to investigate the effects surface stiffness had on economy and leg stiffness (Kerdok, Biewener, McMahon, Weyand, & Herr, 2002). Surface stiffnesses covered a broad range where a theoretical 75 kg runner would deflect the surface 1.8 mm to 22.4 mm for the extreme stiff and soft conditions respectively (assuming 2.3 times body weight exerted at midstance). A 12.5 fold reduction in surface stiffness resulted in runners increasing leg stiffness ($k = F/\Delta L$) by 29% and a 12% reduction in metabolic rate. Authors believe adjustments to leg stiffness to be a strategy to maintain the overall support mechanics. Maintaining these mechanics allows little variation between COM vertical displacements while running on the range of surface stiffnesses.

Likely due to task specific differences, Bishop et al., (2006) showed stiffness results contrary to Divert et al.'s (2005a), i.e. greater leg stiffness when shod. Subjects hopped either barefoot, wearing a low cost jogging shoe ($10) or a cushioned high mileage trainer ($65). When subjects hopped, leg stiffness increased when wearing footwear. This makes intuitive sense if one assumes subjects are trying to maintain overall "system" stiffness as Kerdok et al. (2002) found. The participants would need to increase their leg stiffness with a softer medium, such as what the cushioned trainer would provide. Participants were able to maintain flight times, potentially through manipulating leg stiffness.

Ferris et al. (1999) found that changes to leg stiffness occur rapidly when running on surfaces with different stiffness. In this study, subjects ran over a consistent runway surface before and after a force platform. The platform was covered with a different material (and hardness) than was the runway. Subjects had many practice trials and therefore were prepared for the surface characteristics of the runway and the force platform. This may not be applicable to the real world, since surface changes maybe unexpected. When a runner is very certain of a stiffness change, it may be easy to adjust leg stiffness. What may be more interesting is how quickly subjects would be able to adjust when unaware of surface stiffness characteristics.

Kinematic Adjustments

Given the plethora of differences between barefoot and shod running already discussed, it should not be a surprise that there are also kinematic differences. Why humans run differently barefoot and shod may relate to the deformation of the fatty heel pad (De Clercq, et al., 1994). De Clercq et al. found that in heel toe barefoot running, the heel pad is rapidly deformed to a physiological maximum. This deformation is proportional to the load placed under the plantar surface of the heel. Subjects were shown to touchdown with a much more horizontal foot by De Wit et al. (2000) when running barefoot compared to shod. The difference was quite large (14º). This change was attributable to greater plantar flexion of the ankle joint as well as a more vertical leg at contact. The vertical leg position was obtained through knee flexion as the thigh orientation was similar between the two conditions. A flatter foot placement would disperse pressure to a larger surface area, effectively reducing the acute force applied to the heel region. This may reduce the deformation of the heel pad. It was shown by De Wit et al. that in barefoot running, the maximal local pressure under the heel correlates negatively with the sole angle at touchdown. In other words, a more horizontal foot results in reduced pressure at the heel.

The knee was discovered to be flexing more rapidly at contact when barefoot compared to the shod condition which could lead to a smaller contact velocity as has been shown for barefoot running (De Wit, et al., 2000; Koning & Nigg, 1993). The flexion was initiated as early as 0.02 s before touchdown. These findings are somewhat surprising since others have shown barefoot running to result in greater leg stiffness and shod running utilize knee flexion to attenuate shock more than barefoot running (Divert, et al., 2005a). De Wit et al. (2000) claim this may be a strategy to reduce effective mass of the system in order to reduce impact loading. This increase in knee flexion velocity has also been shown when subjects ran in footwear of differing hardnesses as well. When running in harder footwear, Clarke et al. (1983) found subjects to increase knee flexion velocity. Wright et al. (1998) found similar changes through simulation but believe they are passive changes rather than active adaptations. During initial ground contact, Clarke et al. found the knee in shod running goes from more extended to more flexed compared to barefoot running. The more flexed position during shod running continues throughout midstance. This in part may explain the delayed impact peak in shod running compared to barefoot running in Clarke et al.'s study (33 versus 11 ms). By the end of the stance phase into push-off, differences seem to dissipate and both conditions are similar.

Barefoot runners land more neutral than shod runners who land with a more inverted ankle joint complex (De Wit, et al., 2000). Following contact, kinematic differences still exist between barefoot and shod. From contact to peak GRFv, the ankle goes through a smaller vertical displacement during this deceleration phase when barefoot. De Wit et al. (2000) attribute this one centimeter difference to the absence of a deformable shoe and a smaller plantar flexion ROM for barefoot running.

Stride Length and Stride Frequency

Given the more vertical leg position at contact for barefoot running, the stride length may be reduced (De Wit, et al., 2000). In order to maintain a constant speed, a reduced stride length would require an increase in stride frequency. Stride frequency has been shown to be significantly greater for barefoot running compared to running in TTF (1.48 Hz compared to 1.41 Hz) (Divert, et al., 2005b). In another study, Divert et al. (2005a) showed flight times to be less in barefoot running when compared to shod running. Squadrone and Gallozzi (2009) discovered similar differences for flight time. These results may be related to the increased leg stiffness for barefoot running. Given a greater stride frequency, there may be insufficient time for joints to go through a large ROM. This may necessitate kinematics which allow impact force modulation through a relatively small ROM. One such motion is pronation.

Rearfoot Motion and Tibial Internal Rotation

Tibial rotation coupled with rearfoot eversion is of interest due to possible associations with patella-femoral pain, shin splints, and Achilles tendon pain (Clement, Taunton, Smart, & McNicol, 1981; Eslami, Begon, Farahpour, & Allard, 2007; Smart, Taunton, & Clement, 1980; Tiberio, 1987; Viitasalo & Kvist, 1983). Eslami et al. had subjects run across a forceplate (controlled at 170 steps per minute) in running sandals and barefoot while collecting kinematic data using skin mounted reflective markers. Authors found insignificant differences in rearfoot and tibial motion. They also found peak eversion angles of approximately 11 degrees for both conditions. Peak tibial internal rotation was found to be about 5.2 degrees in both cases. Stacoff et al. (2000) found something similar using bone pins. It should be noted that Stacoff et al. (1991) did find differences between barefoot and shod where running in footwear resulted in increased pronation compared to barefoot. These results have not been consistent.

Another way to examine the coupling relationship between the rearfoot and the tibia is to use a rearfoot eversion and tibial internal rotation excursion ratio or EV/TIR (DeLeo, Dierks, Ferber, & Davis, 2004). In this ratio, a higher number means more subtalar eversion for a given amount of tibial internal rotation. Ratios are generally between 1 and 2 (McClay & Manal, 1997; Stacoff, et al., 2000). This ratio has been shown to be similar by most authors for barefoot and shod running. Eslami et al. (2007) findings of EV/TR ratios for barefoot and shod running of 1.8 and 2.24 respectively are not statistically different. These results are consistent with the findings of Stacoff et al. using bone pins. However, Stacoff et al (1991) found something different. Methodological differences are likely the cause of these discrepancies. Bone pin studies are widely considered the "gold standard." Given several authors, including a bone pin study, have shown no differences between barefoot and shod, this is assumed to be accurate.

Pohl et al. (2006) found no difference in TIR values when using a cross-over stride to induce increased eversion. They also found frontal plane motion of the forefoot and rearfoot to not be as highly correlated as frontal plane motion of the rearfoot is to transverse plane motion of the tibia (Pohl & Buckley, 2008). The mass of the body may "lock" the subtalar joint together whereas the forefoot and rearfoot are not forced together. The foot also contains many bones creating many locations for articulation to occur. The subtalar joint has fewer locations for articulation to occur. The cross-over step resulted in the largest correlation between the rearfoot and the leg. Normal running and adopting a wide running stance resulted in a time shift between eversion and internal rotation. Pohl et al. mention this makes the argument that the loading forces may be rearfoot to tibia coupling and not geometry alone.

Oxygen Consumption

Many have also attempted to answer whether running barefoot or running in TTF is favorable in terms of economy. Most superficially, barefoot running or running in minimal footwear might be energetically superior to TTF due to mass effects. It has been documented that increasing mass at the foot has negative consequences to oxygen consumption (Frederick, 1985; Martin, 1985). Divert and colleagues found reduced VO_2 when barefoot running was compared to running in diving socks with 350 grams of mass added and shoes weighing 350 grams (Divert, et al., 2008). No differences were found between barefoot running and the same socks with 150 grams added and shoes weighing 150 grams. Squadrone and Gallozzi (Squadrone & Gallozzi, 2009) found trained barefoot runners did not require more oxygen when running in TTF with a mass of 341 g compared to barefoot. Frederick and colleagues found barefoot running to require less VO_2 than some shoes, and more than others. These shoes utilized different midsole materials and hardnesses of the midsole foams (Frederick, Clark, Larsen, & Cooper, 1983). Theoretically running with mass added to the foot should require more oxygen than without mass added, but as this research shows; finding consistent evidence has been difficult.

Some believe a forefoot strike pattern should be economically superior to a heelstrike footfall pattern. Forefoot strike patterns are characterized by lower impact forces and high pre-activation levels of plantar flexors (Cavanagh & Lafortune, 1980). The increased pre-activation could facilitate a reduced oxygen cost of running barefoot.

This may increase the elastic energy storage of the tissues. A forefoot strike pattern may also allow some elastic energy storage simply by the application of impact forces causing an eccentric situation at the plantar flexors. Divert et al. (2005a) support the notion that barefoot running is more economical than shod running (Burkett, Kohrt, & Buchbinder, 1985). This claim comes from the negative relationship between musculo-tendinous stiffness and oxygen cost of running (Dalleau, Belli, Bourdin, & Lacour, 1998). Haseqawa et al. (2007) showed more high level distance runners (in a single race) using a midfoot or forefoot landing, and exhibiting shorter contact times. Shorter contact times have also been shown to result in greater storage and release of energy (Ardingo, Lafortune, Minetti, Mognoni, & Saibene, 1995). Not everyone agrees with this idea. Williams et al. (1987) showed higher running economy for heel toe running. They suggest heel toe runners tend to rely on footwear and skeletal structures to manage load which reduces the muscular contribution resulting in better economy. Two additional areas which could provide relevant information to oxygen cost are the energy return capabilities of the body's tissues and footwear, and the amount of internal and external work performed while barefoot and shod.

Energy Return

Shorten (1989) discussed the possibility of energy return from footwear. He noting the potential energy return capabilities of the footwear compared with the elastic properties of the body are minimal. Overall, the shoe dissipates energy with the majority of the dissipation occurring spatially at the heel and temporally at impact. This is the area (both spatially and temporally) where most simulation studies have focused which limits the amount of energy return they can predict (Shorten). It is estimated that 10 – 15

J of energy is possibly stored and recovered during a running step (D. J. Stefanyshyn & Nigg, 2000a). The actual amount depends on the material properties of the footwear and the plantar pressure distribution. For any energy return to be useful, it must occur when the center of mass (COM) is anterior to the support leg, propelling the athlete forward. When the COM is anterior, the heel of the footwear is normally not even in contact with the ground. Thus, any gain in energy return would likely have to occur in the forefoot of the midsole. For this reason and others, Stefanyshyn et al. estimated the amount of actual energy available to influence performance positively to be only 4 – 6 J. They also estimated 30% of this energy is lost due to heat and whether the remaining 70% is useful is dependent on many things including timing, frequency, location, direction. The useful energy return capacity of the footwear midsole seems to be very minimal.

If the footwear midsole cannot provide useful energy return, the potential energetic benefits of barefoot or minimal running may be more important. The theoretical benefits to lighter footwear have already been addressed. In addition, a minimal shoe could return more energy if it forces the athlete to adopt a midfoot/forefoot strike pattern, which may yield elastic storage of energy in the plantar flexors, arch of the foot, and heel fat pad. The possible energy return capability of these structures of the body have been estimated at 42 J (R. M. Alexander & Bennet-Clark, 1977) for the Achilles tendon, 17 J (Ker, Bennett, Bibby, Kester, & Alexander, 1987) for the ligaments of the arch of the foot, and 7-9 J (R. M. Alexander, 2000) for the heel pad. Ardigo and colleagues (1995) found, in a study where people ran with a forefoot strike pattern and a heel strike pattern, that the energetics were similar. However, this is a difficult study to interpret because if subjects aren't accustomed to running with a specific foot strike pattern, energetics may suffer.

Work

Divert et al. (2008) found total work to be significantly lower in shod running compared to simulated barefoot running (diving sock) while $V0_2$ was not different. This may indicate worse economy when shod (less work but equivalent $V0_2$). Since the barefoot condition may have resulted in a more flat foot placement or migration towards a midfoot/forefoot strike pattern (De Wit, et al., 2000), this may be in agreement with what Ardingo et al. (1995) found. Ardingo and colleagues found greater total work (internal + external) for forefoot running compared to heel toe running. The foot strike assumption may be valid as 9 of 12 subjects showed no GRF passive peak (often associated with midfoot/forefoot running) when running in the barefoot condition (diving socks) (Cavanagh & Lafortune, 1980). Therefore, barefoot running required greater mechanical work; however, the economy may have also been reduced leading to similar $V0_2$. Conversely, running in shoes is sometimes economically similar to barefoot running, even though the footwear are relatively heavier. The relatively heavier footwear require more VO_2 because of mass effects, but if these mass effects were not present, barefoot running could require greater oxygen consumption. Modifications to running kinematics due to wearing a shoe influence the work performed, net economy of the system, and possibly oxygen consumption although consistency of results has been elusive.

In summary, a great deal of research has taken place exploring the differences between barefoot and shod running. Loading rate has been shown to increase when barefoot. Tibial accelerations have shown increases when barefoot, corresponding to reduced effective mass. Leg stiffness is increased when barefoot but firm surfaces compared to soft surfaces may not agree. Barefoot kinematics tend to show a flatter foot placement and reduced stride length. Oxygen consumption should be reduced when barefoot as a result of reduced mess but consistent findings have been elusive.

In addition to barefoot versus shod comparisons, we can assume more minimal footwear will be less cushioned, lighter weight, more flexible, and have a thinner midsole. Research related to footwear investigating these characteristics might be relevant to running in minimal footwear.

Midsole Cushioning

When a mechanical impact test is performed on a soft midsole and a hard midsole the differences are obvious. A mechanical impact tester drops a known mass from a known height onto the midsole while force and displacement information is recorded (Cavanagh, 1981). Clarke and colleagues using two pairs of footwear identical except for midsole hardness examined cushioning in this fashion. These footwear were considered extremes in softness and hardness in the footwear industry at the time (Clarke, Frederick, & Cooper, 1983). The mechanical impact scores were 50% different, with the hard midsole resulting in a greater peak force which occurred earlier (time).

The effect of midsole hardness on the GRF vertical impact peak is not clear. In theory, a softer midsole would result in a reduced vertical impact peak of the GRF. Showing this experimentally has been elusive however. Nigg and colleagues used six shoes of varying hardness and found the hardness of the footwear was not correlated to impact peak magnitudes (B. M. Nigg, et al., 1983). Subjects appeared to adjust kinematics to the material properties of the footwear. The Clarke paper previously discussed showed similar results between the two shoes at the opposite ends of the cushioning spectrum (Clarke, Frederick, & Cooper, 1983). Although no differences were found in peak magnitude of vertical ground reaction force, the time from contact to reach this peak was significantly greater for the soft midsole as would be expected given mechanical tests. Hennig et al. (1996) actually found the impact peak to be reduced when subjects wore firm footwear compared with softer footwear. Subjects seemed to respond to the perception of reduced cushioning with more forefoot loading. This is similar to what was found in barefoot versus shod comparisons, and it is clear that athletes/runners are well equipped to adjust kinematics due to different surfaces and footwear.

Mean power frequency (MPF) has been shown to be greater in barefoot running compared to shod running, and results from midsole hardness studies seem to agree if barefoot is treated as similar to a harder midsole. In the Hennig et al. (1996) study, a relatively hard midsole resulted in more horizontal footstrikes, thereby reducing or maintaining the impact peak. Results also showed increases in the MPF of impact with a hard midsole (Hennig, et al., 1996; Milani, Hennig, & Lafortune, 1997). Leg stiffness may have been increased resulting in a MPF increase as discussed with barefoot running. Milani et al. (1997) also found MPF to correlate well with the perception of impact severity. This could either mean subjects sensed large impacts and adjusted leg stiffness (and therefore MPF) or the sensation of severe impacts was due to large MPF.

Summarizing the midsole hardness literature seemingly relates well to barefoot versus shod results. Subjects are able to adjust running pattern to accommodate midsole hardness as they were shown to do when barefoot. The mean power frequency was also shown to increase with a harder midsole.

Shoe Mass

Another obvious difference between traditional TTF and minimal footwear is mass difference. In theory, a minimal shoe would be constructed with less material which should make it lighter. Studies focused on mass increases associated with footwear have shown adding mass to the foot increases the oxygen cost of running. Frederick showed that adding 100 g per foot added 1% to oxygen cost and Martin found something similar (Frederick, 1985; Martin, 1985). They conclude that this may be as simple as the mass increasing the amount of mechanical work, resulting in increased oxygen cost. Divert et al. (2008) confirmed this using weighted diving socks and weighted footwear to conclude that differences in O_2 were simply due to mass differences at the foot.

Divert et al. (2008) also found leg stiffness to vary with mass on the foot. In the shod condition, the active GRF peak didn't change between the mass conditions, but the vertical stiffness did. They found the vertical oscillation of the COM was increased with mass added to footwear. Stride frequency was also shown to be reduced when mass was added, which was consistent with Martin's work (1985).

Oxygen cost, leg stiffness, and stride frequency have been shown to be altered by mass on the foot. Minimal footwear will likely have reduced mass compared to TTF. This mass reduction may result in a reduction in oxygen cost and an increase in vertical stiffness and stride frequency.

Midsole Thickness

In theory, a minimal shoe would have a thinner midsole than TTF. In terms of midsole thickness and running footwear, the literature is pretty bare. TenBroek et al. (2006) showed that a thicker midsole produced greater inversion during cutting maneuvers. Robbins and colleagues believe thick EVA in modern running footwear necessitate a large impact force in an attempt to transform the interface into a more stable surface (Robbins & Waked, 1997a). Balance has also been shown to suffer with thick soft footwear (Robbins, et al., 1997). Robbins et al. used a balance beam and 17 subjects with a mean age of 33 yrs to show that a thin, hard midsole lead to improved balance scores. Thus, a minimal shoe may result in less frontal plane ankle motion, reductions in impact forces, and improved balance.

Flexibility

A shoe with less "substance" and a thinner midsole should result in a more flexible shoe. Research has been done on medial longitudinal bending stiffness and the effect on running shoes and runners. A stiffer shoe was shown to reduce energy lost at the metatarsophalangeal joint (D. Stefanyshyn & Fusco, 2004; D. J. Stefanyshyn & Nigg, 2000b). Through oxygen consumption analysis, authors discovered there is an ideal stiffness and too stiff is counterproductive (Roy & Stefanyshyn, 2006). These 'ideal' stiffnesses are certainly greater than what is expected in minimal footwear. The benefits of the Nike Free discussed earlier are likely related to the flexibility of these shoes. This seems counterproductive as flexible footwear increased muscle activity and strength but less flexible footwear were more efficient. Nonetheless, minimal footwear could be used for training purposes to increase muscular size and strength.

Fatigue

The majority of footwear research is conducted while subjects are in an idealized situation. Subjects are typically well accustomed to the testing procedure and are not fatigued which may not be realistic compared to a typical training run. Some researchers have studied footwear and its interaction with the body while subjects are fatigued to some degree, which is when overuse injuries are thought to occur (Butler, Hamill, & Davis, 2007). While in a fatigued state, the body may conserve metabolic energy by not utilizing the muscle's shock attenuation capacity, instead using the passive structures or not attenuating as well (Mercer, Bates, Dufek, & Hreljac, 2003; Nordin & Frankel, 1989). It has also been reported that bone strain rate and magnitude likely change with fatigue in addition to changes in strain location (Burr, 1997; Grimston & Zernicke, 1993).

Gerlach et al. (2005) collected vertical GRF data before and after 90 adult females performed an exhaustive treadmill run. They found a six percent decrease in impact peak and an eleven percent decrease in loading rates after the run. Interestingly, those whom had a previous injury had less reduction in impact loading rate compared with healthy runners. Authors maintained contact with all subjects for one year to determine if these fatigue related reductions in impact loading rate were linked to future injury potential. It was determined that those who did not alter loading rate with fatigue likely did so due to previous injury as there was no differences in injury numbers over the course of a year (Gerlach, et al.). The findings of decreased impact forces were consistent with other research (Nicol, Komi, & Marconnet, 1991; Paavolainen, Nummela, Rusko, & Hakkinen, 1999). Conversely, some have found increased impact forces post fatigue (Dickinson, Cook, & Leinhardt, 1984). Hardin and Hamill (2002) showed during a prolonged downhill run, peak tibial acceleration increased after 5 minutes of a 30 minute run and stayed elevated. Whether these recreational runners were experiencing fatigue after 5 minutes is unknown. Another possibility is that the footwear has changed during this five minutes, as has been shown previously (Divert, et al., 2005a). Divert et al. found midsoles to become firmer during the first four minutes of a treadmill run. A firmer midsole could result in increased peak tibial accelerations as were shown by Hardin and Hamill. Yet another study found loading rate results were related to which muscles were fatigued (Christina, White, & Gilchrist, 2001). Fatigue was induced locally in this study on either the invertors or dorsiflexors of the foot. Loading rate was found to increase with dorsiflexion fatigue and impact peak magnitude to decrease following inverter fatigue (Christina, et al.).

Research on the effect of fatigue on tibial accelerations has been more consistent. Both Derrick et al. (2002) and Verbitsky et al. (1998) found increases in tibial acceleration with fatigue. These findings may or may not relate to increased impact forces as evident from the section on effective mass (Derrick, et al.). Verbitsky et al. also found decreased stride frequency during this fatigued state. In order to maintain a constant speed with decreased stride frequency, an increase in stride length is necessary. Increased tibial accelerations have been previously shown to occur with increases in stride length, therefore this result is not surprising (Mercer, Devita, Derrick, & Bates, 2003). Conversely, Willson and Kernozek (1999) found increases in cadence when fatigued, implying a decrease in stride length. They also found greater forefoot loading and reduced heel loading with fatigue (Willson & Kernozek). Given previous findings on foot strike patterns, these results seem to be related to the increased step frequency typically seen in a more midfoot/forefoot touchdown pattern (Divert, et al., 2005a; Divert, et al., 2005b). Other kinematic changes have also been shown to occur when running in a fatigued state, which are likely related to these acceleration findings.

Effective mass has been shown/predicted to vary with knee angle and ankle complex angle. As mentioned earlier Denoth (1986) suggests the knee has the greatest effect on effective mass at about 160-170º. Derrick et al. (2002) found the knee angle to be in that range at the start, in the middle, and at the end of an exhaustive run. The knee was found to be more flexed at the end of the run compared to the beginning. The tibial acceleration results seem to correspond with these results. In theory, a more flexed knee would result in less effective mass, and greater tibial accelerations (Derrick, et al.). The rearfoot angle also has the potential to affect effective mass and possibly tibial acceleration as previously mentioned (Valiant, 1990). Derrick et al found the rearfoot angle at contact to be greater in the fatigued state. This result could also contribute to the increased tibial accelerations. A greater inversion angle at touchdown could result in decreased effective mass and greater tibial acceleration. Yet another example of effective mass manipulation was shown in a study by Mizrahi et al. (2001) who showed increased ankle dorsiflexion during stance as well as more vertical excursion of the hip over a 30 minute run.

Butler et al. (2007) looked into matching subjects to a cushioned training shoe or a motion control shoe using an arch height index measure. Subjects ran for 30-45 minutes at a self selected pace designed to produce fatigue as measured using perceived exertion and heart rate. Fatigue was found to increase tibial internal rotation in the low arched runners for the cushioned trainer and decrease tibial internal rotation for the motion control footwear. They found no fatigue effects for high arched runners, but did find reduced peak tibial acceleration in the cushioned trainer compared to the motion control footwear (Butler, et al.).

Fatigue caused by running likely results in a decrease in GRF loading rate and impact peak. Tibial acceleration has conversely been shown to increases post fatigue. A more flexed knee and more inverted ankle at TD, which Derrick et al (2002) show, are probably related to these increases in acceleration given the effective mass discussion previously. Also, matching footwear to runners based on arch height index might restrict fatigue effects related to tibial internal rotation.

Summary

Minimal footwear may take advantage of the proposed advantages of barefoot running and TTF. As mentioned in the introduction, overall the literature is limited regarding how runners will respond to running in minimal footwear from the first step to many repetitive impacts. The literature on barefoot versus shod running is likely related as is the research on footwear characteristics including midsole hardness, footwear flexibility, and the mass of footwear. This chapter has summarized this relevant literature to provide background as to how runners may react to minimal footwear.

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CHAPTER III

METHODOLOGY

Introduction

This series of research studies investigates the effect footwear cushioning amount and running surface have on running patterns. While the majority of runners wear traditional training footwear (TTF), there are some runners who train barefoot for the majority of their runs. Each of these may have potentially negative effects as some believe TTF to be overbuilt while barefoot running exposes athletes to environmental dangers. A potential solution may be a minimal shoe, taking advantage of the potential benefits from both training conditions. These experiments will utilize a treadmill with foam added to the belt, as well as identical footwear with varying midsole thickness to investigate how a runners accustomed to running in TTF react to various amounts and applications of cushioning.

Subjects

Data from the literature was used to estimate sample size for a minimum statistical power of 80% with an alpha level of 0.05 (De Wit, et al., 2000). Sagittal plane dependant variables utilized in the power analysis included ankle angle, sole angle, leg angle, and the knee angle all at TD. For this reason, ten injury free, recreational male runners between the ages of 18 and 55 who used a rearfoot footfall pattern participated in each study. Approval for the project was granted through the University of Massachusetts Human Subjects Review Board and each subject filled out an informed consent form and a Physical Activity Readiness Questionnaire prior to participation.

Experimental Set-up

A very similar experimental set-up was used for each of the three studies. Running kinematics were obtained at 200 Hz using a Qualisys Oqus motion capture system (Oqus 500, Qualisys AB, Gothenburg, Sweden). The calibration object was L-shaped with 4 markers of known locations. This calibration object established the fixed right hand lab coordinate system where positive Y was the direction of progression and positive Z was up. A wand with two markers of known locations was also used to scale the individual camera views within the camera volume. Cameras were calibrated using Qualisys Track Manager Software (Qualisys AB, Gothenburg, Sweden), and calibration errors were below 0.6 mm for each camera.

All running was done on a Woodway treadmill (Woodway, Waukesha, WI). This treadmill was motorized and had an aluminum slat belt. The treadmill belt was 22 inches wide by 68 inches long (Figure 1).

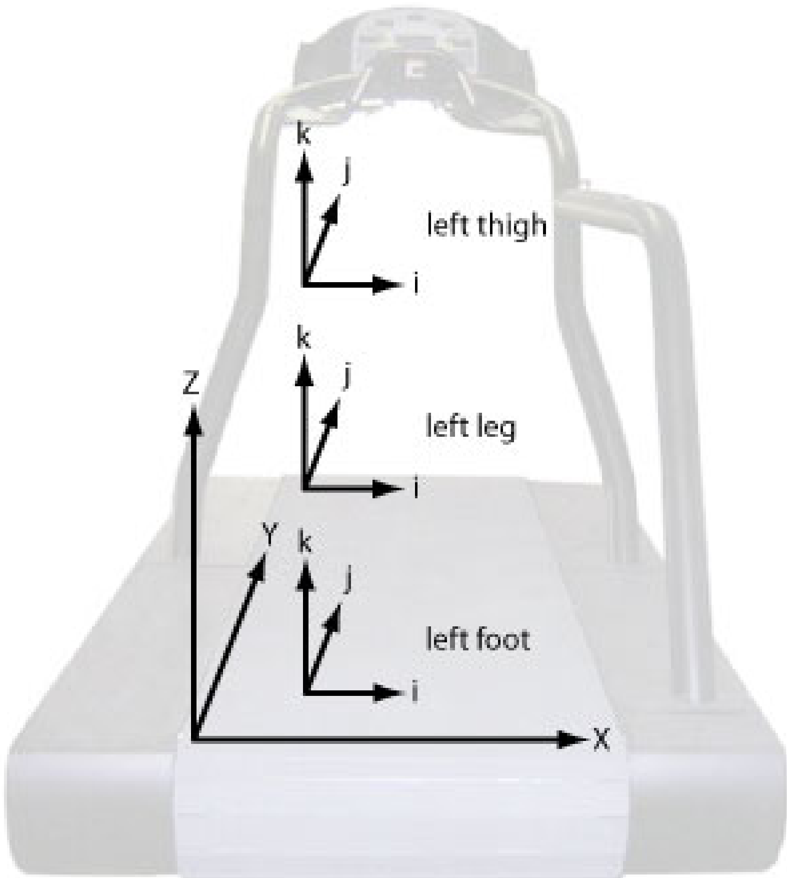

Figure 1. Orientation of the global orthogonal coordinate system on the treadmill. Also shown is the approximate orientation of the local segment coordinate systems on the left lower extremities.

Acceleration signals were captured at 1000 Hz using Delsys accelerometers (Delsys Incorporated, Boston, Massachusetts). One accelerometer was attached rigidly to the inferior, antero-medial leg on the left tibia and another attached rigidly to the anterior aspect of the forehead. The accelerometers were attached securely to the skin using 2-sided tape and were further wrapped with athletic pre-wrap to subject tolerance. For the tibial accelerometer, the vertical axis of the accelerometer was aligned with the long axis of the leg. For the head accelerometer, the vertical axis of the accelerometer was aligned roughly with the lab coordinate system's z-axis.

Study 1: Cushioning Mode and Magnitude Affect Treadmill Running Patterns

Five running conditions were used to manipulate magnitude of cushioning and mode of cushioning (Figure 2). Magnitude of cushioning represents the amount of shock attenuation the condition provides to the runner. Magnitude of cushioning was quantified using an Exeter Research gravity driven impact tester (Exeter Research, Inc., Exeter, NH) and by following ASTM standard F1614-99.2006 (Procedure A). Mode of cushioning represents how this shock attenuation was provided. One mode of cushioning included providing shock attenuation through footwear (two conditions: 18-F & 30-F), and the other mode of cushioning was to apply shock attenuation through the running surface (two conditions: 18-S & 30-S). A final condition required subjects to run barefoot on an un-cushioned running surface. Footwear conditions included a production New Balance 1062 (New Balance Athletic Shoe, Inc., Boston, MA) neutral cushioning TTF with 30 mm of total heel foam and 15 mm of total forefoot foam when both the midsole and the insole were considered (Table 1). The other footwear condition was specifically constructed for the experiment. It utilized a New Balance 790 upper which was a lightweight upper with a very minimal heel counter. The midsole of this footwear was composed of cut and buff ethlylene-vinyl acetate (EVA) with an average hardness of 61 Shore 00. Total heel thickness was 18 mm and total forefoot thickness was 13 mm again including the midsole and insole. On the bottom of the footwear, the lateral heel and the medial forefoot had a single basic layer of rubber outsole material attached.

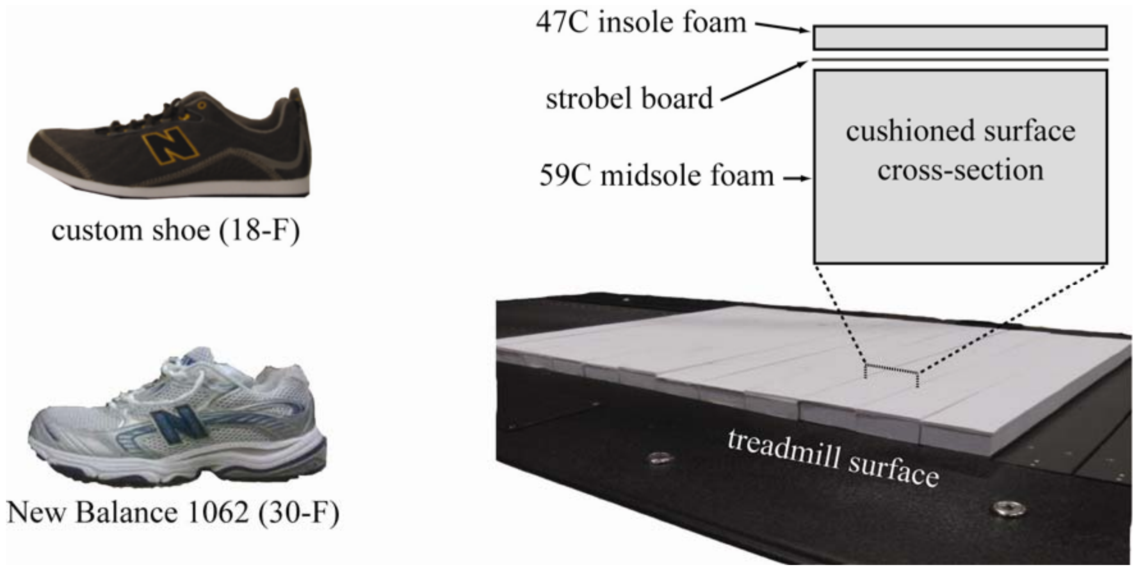

Figure 2. Illustration of footwear conditions and cushioned running surface.

Table 1. Thickness measurements of underfoot layers for footwear conditions and surface conditions. Cushioning properties of conditions were compared using a peak g score.

Part thickness and peak g impact score for conditions					
	thickness (mm)				
condition	insole	strobel	midsole	total	peak g
18-S	5	1	12	18	12.5
18-F	3	1	14	18	15.3
30-S	5	1	24	30	11.2
30-F	5	1	24	30	10.4

The two surface conditions allowed subjects to run barefoot on a cushioned treadmill surface. These conditions were created to roughly match cushioning properties of footwear. This surface was achieved by adhering foam slats directly onto the treadmill belt (Figure 2). Both surface conditions consisted of a of 59 Shore 00 durometer foam, glued to a one millimeter thick strobel material, which was glued to five millimeter 47 Shore 00 durometer foam. The only difference between the two surface conditions was the thickness of the 59 Shore 00 foam (12 mm and 24 mm). The fifth condition (barefoot) involved running barefoot on the aluminum treadmill belt. The magnitude of cushioning of footwear conditions and surface conditions were compared using peak g score (Table 1) obtained using a gravity driven impact tester and are as follows: 18-S – 12.5 g, 18-F – 15.3 g, 30-S – 11.2 g, 30-F – 10.4 g.

Study 2: Response and Acclimation to Treadmill Running in Minimal Footwear

Three pairs of specifically constructed footwear were used in this study (Figure 3). All footwear utilized a New Balance 790 upper, a lightweight upper with a very minimal heel counter. The midsole of this footwear was composed of cut and buff ethlylene-vinyl acetate (EVA) with an average hardness of 61 Shore 00. Each of the three pairs of footwear had distinctly different EVA thicknesses (Figure 3). One shoe had a typical TTF thickness, one simulated very minimal, barefoot inspired footwear, and one fell between the dimensions of the previous two. On the bottom of the footwear, the lateral heel and the medial forefoot had a single basic layer of rubber outsole material attached. Cushioning properties of footwear conditions were compared using a peak g score obtained using a gravity driven impact tester and were as follows: thin – 40.1 g, medium– 16.8 g, thick – 14.3 g (Exeter Research, Inc., Exeter, NH) (Figure 3).

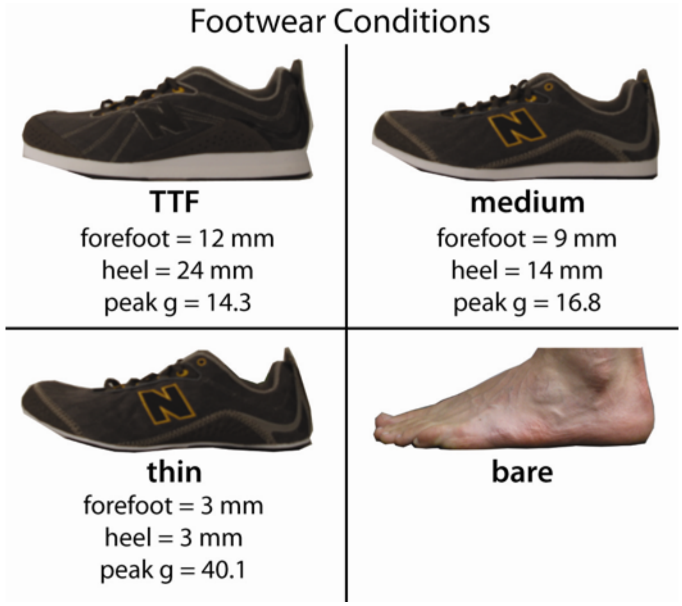

Figure 3. Footwear conditions utilized in the study. Foam thicknesses (mm) and peak g impact scores are presented.

Study 3: Response to a Sustained Run in Minimal Footwear

Three pairs of specifically constructed footwear were used in this study. These footwear all utilized a New Balance 790 upper, a lightweight upper with a very minimal heel counter. The midsole of this footwear was composed of cut and buff ethlylene-vinyl acetate (EVA) with an average hardness of 61 Shore 00. Each of the three pairs of footwear had distinctly different EVA thicknesses (Figure 4). One shoe had a typical TTF thickness, one simulated very minimal, barefoot inspired footwear, and one fell between the previous two midsole dimensions. On the bottom of the footwear, the lateral heel and the medial forefoot had a single basic layer of rubber outsole material attached. Cushioning properties in the rearfoot between footwear conditions were compared using a peak g score obtained with a gravity driven impact tester and were as follows: thin – 40.1 g, medium– 16.8 g, thick – 14.3 g (Exeter Research, Inc., Exeter, NH) (Figure 4).

Figure 4. Footwear conditions utilized in the study. Foam thicknesses (mm) and peak g impact scores are presented.

Protocol

On each visit to the lab, subjects performed a standard treadmill warm up prior to beginning data collections. Retro-reflective markers were attached using two sided tape to the subjects left and right greater trochanter, left medial and lateral femoral condyle, left medial and lateral malleolus, and left 1st metatarsal head and 5th metatarsal head. These markers were used as calibration markers within Visual3D (C-Motion, Inc., Germantown, Maryland). Tracking markers were attached via rigid shells to the heel of the footwear (or the skin on the heel), the leg, and the thigh. The two Delsys accelerometers were also attached on each visit as previously discussed.

Study 1: Cushioning Mode and Magnitude Affect Treadmill Running Patterns

Subjects ran at 3.0 m/s for six minutes in each of the five conditions previously described (Figure 2). Between runs, subjects rested until they reported readiness and running conditions were prepared (Hardin, et al., 2004). A key aspect of this study was subjects having modest information about each footwear condition before running. Subjects were not allowed to walk or run in any footwear condition before the test started. To accomplish this, immediately after the test administer put the footwear on the subject, they stood up and boarded the treadmill.

Study 2: Response and Acclimation to Treadmill Running in Minimal Footwear

All runs were performed at 3.0 m/s for six minutes in each of four conditions previously discussed (Figure 3). Between runs, subjects rested until they reported readiness and running conditions were prepared (Hardin, et al., 2004). A key aspect of this study was subjects having modest information about each footwear condition before running. In order to investigate how subjects adjust from their first step in a new shoe, subjects were not allowed to walk or run in any condition before mounting the moving treadmill. To do this, after the test administrator put the footwear on the subject, the subject stood up, placed his left foot on the side of the treadmill and used his right foot to gauge the speed of the moving treadmill before starting to run. This procedure ensured subjects had as little information as possible before beginning to run.

Study 3: Response to a Sustained Run in Minimal Footwear

Subjects performed all runs at 3.0 m/s for 30 minutes in each of the three footwear conditions previously discussed (Figure 4). For each subject, data collections were done at least one day after the previous collection to ensure sufficient rest from fatigue and impact. A key aspect of this study was subjects having modest information about each footwear condition before running. In order to investigate how subjects adjust from their initial steps in a new shoe to well into a sustained run, subjects were not allowed to walk or run in any footwear condition before the test started. To accomplish this, immediately after the test administer put the footwear on the subject, they stood up and boarded the treadmill.

Data Reduction

Raw XYZ coordinates obtained from Qualisys Track Manager were imported into Visual3D™ software (C-motion, Rockville, MD, USA). The foot, leg, and thigh were all modeled as the frustra of cones. Local right hand coordinate systems and segment end-points were derived for all lower extremity segments using the calibration markers attached during standing calibration trials. The thigh and leg coordinate systems had z-axes approximately parallel to the long axis of the segment. The x-axes were directed medially and the y-axes were directed anteriorly. The foot segment had the y-axis approximately parallel to the long axis of the foot, the x-axis was medial and the z-axis was directed vertically. Segment motions were captured using the tracking markers. All kinematic data were filtered using a dual pass, 2nd order low-pass Butterworth filter with a cut-off frequency of 12 Hz. Segment and joint angles were calculated using an Xyz Cardan rotation sequence (Robertson, Caldwell, Hamill, Kamen, & Wittlesey, 2004).

Raw acceleration data were low pass filtered using the same Butterworth filter with a cut-off frequency of 50 Hz (Boyer & Nigg, 2007). Touchdown (TD) and toe-off (TO) were determined in acceleration signals through visual inspection using recurring spikes in tibial acceleration plots. Each stance phase from acceleration signals had means and linear trends removed (Mercer, Vance, Hreljac, & Hamill, 2002). Power spectral densities (PSD) were calculated on these sections using a Fourier Transformation. The ratio of PSD for the head to PSD for the tibia was calculated for each frequency within the range of 0-20 Hz. Ratios were averaged across these frequencies to describe shock attenuation. Larger ratios indicated more impact shock attenuation (Derrick, Hamill, & Caldwell, 1998; Mercer, et al.; Shorten & Winslow, 1992).

Study 1: Cushioning Mode and Magnitude Affect Treadmill Running Patterns

For kinematic data, TD was determined using heel triad anterior maxima and knee extension maxima were used to determine TO (Fellin & Davis, 2007). The vertical minimums used by Fellin and Davis did not work well with our heel counter triad and therefore forward maxima were utilized. Utilizing the forward position of the lateral heel counter marker to locate TD likely created a virtual TD in kinematic data which occurred early for some. This would have affected many kinematic variables at TD. De Witt and colleagues (2000) overwhelmingly discovered the differences in kinematics between running barefoot and when wearing TTF to be present at TD and 30 ms before TD. Therefore, early estimation of TD was not thought to effect results.

In order to investigate the effect cushioning magnitude had on dependent variables, a graphical continuum was created. The range of this continuum included barefoot on the firm end of the spectrum and the most cushioned 30-F condition on the soft end. The remaining conditions were placed on the continuum in an appropriate location based on cushioning score. When dependent variables implied the firmer conditions were different than softer conditions, cushioning magnitude was expected to be contributing. The continuum was then utilized to display the differences graphically in an attempt to determine whether consistent transition points were present. The size of the tick mark placed on the continuum explained the strength of the differences. A large tick indicated clear statistical differences isolating conditions to the right and left of the tick mark location. As an example, if the barefoot condition resulted in significant differences compared to all other conditions, a large tick was placed on the continuum indicating a significant difference between barefoot and the other conditions. If the statistical difference did not clearly differentiate a condition compared to all others, a smaller tick was utilized.

Study 2: Response and Acclimation to Treadmill Running in Minimal Footwear

For kinematic data, TD was determined using heel triad anterior maxima, and knee extension maxima were used to determine TO (Fellin & Davis, 2007). The vertical minimums used by Fellin and Davis did not work well with our heel counter triad and therefore forward maxima were utilized. Utilizing the forward position of the lateral heel counter marker to locate TD likely created a virtual TD in kinematic data which occurred early for some. This would have affected many kinematic variables at TD. De Witt and colleagues (2000) overwhelmingly discovered the differences in kinematics between running barefoot and when wearing TTF to be present at TD and 30 ms before TD. Therefore, early estimation of TD was not thought to effect results.

In order to evaluate coordination variability, continuous relative phase (CRP) was employed. Position and angular velocities of the foot, leg, and thigh were used to create phase planes which were each normalized to a unit circle to account for amplitude and frequency differences between segments (Hamill, van Emmerik, Heiderscheit, & Li, 1999). Arctangent was then utilized to compute phase angles based on the normalized position and angular velocity time series In order to investigate the relationship between the thigh and tibial internal rotation and the foot and tibial internal rotation, three coupling comparisons were utilized: thigh flexion/extension and tibial rotation ($Th_{F/E}$-Tib_{Rot} – Comparison A), thigh abduction/adduction and tibial rotation ($Th_{Ab/Ad}$-Tib_{Rot} – Comparison B) and tibial rotation and foot eversion/inversion (Tib_{Rot}-$Ft_{Ev/In}$ – Comparison C) (Hamill, et al., 1999). To further investigate sagital plane coordination and the influence of the amount of underfoot cushioning, intralimb couplings for left thigh-left leg (Comparison D) and left leg-left foot (Comparison E) were also calculated (Seay, Haddad, van Emmerik, & Hamill, 2006). All comparisons utilized a proximal minus distal segment convention. Finally, absolute values were used resulting in a CRP measure between 0 and 180° to avoid phase discontinuities. CRP variability was calculated for each subject by condition at each time epoch using stride-to-stride standard deviations in CRP.

To test for a main effect for time, time epochs were created for each minute on the treadmill. Because runners boarded a moving treadmill, the initial steps on the treadmill were often unnatural. Utilizing acceleration traces, the first step that appeared qualitatively similar to steps farther into the run was utilized as the initial step in the analysis. This step was also defined as the first in kinematic data. Typically one or two steps immediately following getting onto the treadmill were not included in the analysis. Ten steps immediately following the defined first step were used to create time epoch 1. Ten steps at the beginning of each subsequent minute on the treadmill were utilized to create remaining time epochs.

To look more closely at the initial time on the treadmill, a moving window analysis was utilized to investigate if standard deviations were reduced over the first 20 steps on the treadmill. A five point moving window was utilized to calculate average standard deviations of acceleration dependent variables over five step increments. Steps one through five made up the first moving window. Steps two through six made up the second. This trend continued with steps 15 to 20 making up the final window. The average standard deviations for these windows were compared to determine if the variability of acceleration signals changed drastically over the course of the initial 20 steps on the treadmill. This would indicate a stabilization of movement patterns.

Study 3: Response to a Sustained Run in Minimal Footwear

For kinematic data, TD was determined using maximum forward position of the heel triad, and knee extension maxima were used to determine TO (Fellin & Davis, 2007). The vertical minimums used by Fellin and Davis did not work well with our heel counter triad and therefore forward maxima were utilized. TD was defined, through visual inspection, to be four frames after these forward maxima. Utilizing the forward position of the lateral heel counter marker to locate TD likely created a virtual TD in kinematic data which occurred early for some. This would have affected many kinematic variables at TD. De Witt and colleagues (2000) overwhelmingly discovered the differences in kinematics between running barefoot and when wearing TTF to be present at TD and 30 ms before TD. Therefore, early estimation of TD was not thought to effect results.

In order to investigate the effect time had on running patterns, time epochs were created from each five minutes of the treadmill run. The initial time epoch (time epoch 1) included the first 10 steps once the treadmill was up to speed. The remaining time epochs were created using ten steps at the beginning of each five minutes on the treadmill. Therefore, epoch 2 was data from five minutes into the run; epoch 3 was data from ten minutes into the run, and so on.

Statistical Analysis

Repeated measures ANOVA was used to determine statistical differences with a criterion alpha level of 0.05. When differences were found between conditions, a Tukey multiple comparison test was employed to locate the locus of the differences. SAS statistical software (SAS Corporation, Cary, North Carolina) was used for all repeated measures ANOVA comparisons as well as post hoc tests. Dependent variables were chosen based on a literature review and to help answer the research questions.

Study 1: Cushioning Mode and Magnitude Affect Treadmill Running Patterns

Compared to running in TTF, runners adjust kinematic patterns when barefoot (De Wit, et al., 2000). It is likely some adjustments are made due to the loss of underfoot cushioning. Additionally the "geometry of the foot/ground interface" (De Wit, et al.) changes significantly when comparing TTF to barefoot. There are other possibilities as well. Aside from cushioning changing the impact collision, cushioning also protects the plantar surface of the foot from environmental factors. Additionally, footwear may constrain the foot requiring kinematic alterations unrelated to cushioning, protection, or foot/ground geometry. The extent that geometry changes, plantar surface protection, and constraining the foot affect running pattern change is unclear. If the foot could be protected and cushioned without requiring footwear and the change in geometry often accompanying, our knowledge about constraining the foot and altering the foot/ground interface's geometry may be improved.

Hypothesis 1: To determine if providing the cushioning properties of a TTF using a cushioned running surface can result in a barefoot runner developing a similar running pattern to shod running, dependent variables were calculated for barefoot running on a cushioned surface and shod running on a firm surface during six minute treadmill runs. A 1 way repeated measures ANOVA with footwear/surface condition as the independent variable was used to compare across conditions for the dependent variables. Failure to reject the null hypothesis indicates runners ran barefoot on a cushioned surface with similar kinematic patterns to shod running on a non-cushioned treadmill surface.

Hypothesis 2: To determine if subjects' running patterns change when cushioning properties of the footwear/surface are altered, dependent variables were calculated for several conditions which varied the amount of cushioning provided. Two footwear conditions were utilized. First, a specially constructed shoe with a midsole 14mm thick in the heel and 9 mm thick in the forefoot (plus 3 mm of insole) was used. The second pair was a production New Balance MR1062 TTF. Two cushioned treadmill conditions were also created using materials similar to the footwear used. These surfaces were attached to the treadmill allowing subjects to run barefoot on a surface providing cushioning. All of these conditions varied in terms of the amount of cushioning provided. A 1 way repeated measures ANOVA with footwear/surface condition as the independent variable was used to compare across conditions for the dependent variables. Failure to reject the null hypothesis indicates runners ran similarly in all conditions regardless of the amount of cushioning the conditions provided.

Study 2: Response and Acclimation to Treadmill Running in Minimal Footwear

The great majority of runners wear TTF for running on a day to day basis. There is a possibility wearing minimal footwear may benefit those who are often injured in TTF. Those who run barefoot are at risk for cuts, scrapes, and bruises due to lack of plantar surface protection. Wearing minimal footwear may benefit these individuals by giving them plantar protection without adding substantial weight or midsole. Minimal running footwear sales have encountered rapid growth over the last several years and many product offerings are currently on the market from a variety of manufactures. We do not know how runners will respond to running in something minimal for the first time. It is likely, for many individuals this would be a novel task which requires exploration and learning.

Hypothesis 1: To determine whether running in footwear with almost no cushioning or protection will result in changes in kinematic patterns compared to running barefoot or running with footwear with TTF thicknesses, kinematic dependent variables were calculated over the course of a six minute run for three footwear conditions and a barefoot condition. A 2 way repeated measures ANOVA with footwear condition (barefoot, thin, medium, and thick) and time (ten footfalls during each minute of running) as independent variables was used to compare conditions. Rejecting the null hypothesis indicates runners adjusted kinematic patterns based on footwear worn during the run.

Hypothesis 2: To determine if running in minimal footwear will result in similar shock attenuation to barefoot and running in footwear with TTF thicknesses, peak accelerations and transfer functions were analyzed for tibial and head accelerations across each footwear condition. A 2 way repeated measures ANOVA with footwear condition (barefoot, thin, medium, and thick) and time (ten footfalls during each minute of running) as independent variables was used to compare conditions. Rejecting the null hypothesis indicates shock attenuation varied by footwear condition when subjects ran barefoot, in minimal footwear, and when wearing thicker footwear.

Hypothesis 3: To determine if running in minimal footwear is a novel enough task to result in increased coordination variability compared to running footwear with TTF thicknesses, continuous relative phase was calculated for several coordination comparisons. A 2 way repeated measures ANOVA with footwear condition (barefoot, thin, medium, and thick) and time (ten footfalls during each minute of running) as independent variables was used to compare conditions. Rejecting the null hypothesis indicates coordination variability varied across footwear conditions or time.

Hypothesis 4: To determine how quickly runners adjust kinematic patterns when an unknown footwear condition is introduced, time epochs were compared for the initial ten steps on the treadmill to epochs at each minute on the treadmill. A 2 way repeated measures ANOVA with footwear condition (barefoot, thin, medium, and thick) and time (ten footfalls during each minute of running) as independent variables was used to compare conditions. Rejecting the null hypothesis indicates runners adjusted kinematic patterns at some point during the treadmill run.

Study 3 Response to a Sustained Run in Minimal Footwear

The majority of runners wear TTF for running on a day to day basis. There is a possibility wearing minimal footwear may benefit those who are often injured in TTF. Those who run barefoot are at risk for cuts, scrapes, and bruises due to lack of plantar surface protection. Wearing minimal footwear may benefit these individuals by giving them plantar protection without adding substantial weight or midsole. Minimal running footwear sales have encountered rapid growth over the last several years and many product offerings are currently on the market from a variety of manufactures. We do not know how runners will respond to running in something minimal for the first time. It is likely for many individuals, this would be a novel task which requires exploration and learning. If a very minimal shoe was purchased, a six minute run is likely much shorter than their typical runs wearing this product. It is likely that a consumer would spend 30 minutes or more on their initial run and subsequent runs, in these footwear.

Hypothesis 1: To determine whether running in footwear with almost no cushioning or protection will result in changes in kinematic patterns compared to running in footwear with TTF thicknesses, kinematic dependent variables were calculated over the course of a six minute run for three footwear conditions. A 2 way repeated measures ANOVA with footwear condition (thin, medium, and thick) and time (ten footfalls during each five minutes of running) as independent variables was used to compare conditions. Rejecting the null hypothesis indicates runners adjusted kinematic patterns based on footwear worn during the run.

Hypothesis 2: To determine if running in minimal footwear will result in similar shock attenuation to running in footwear with TTF thicknesses, peak accelerations and transfer functions were analyzed for tibial and head accelerations across each footwear condition. A 2 way repeated measures ANOVA with footwear condition (thin, medium, and thick) and time (ten footfalls during each five minutes of running) as independent variables was used to compare conditions. Rejecting the null hypothesis indicates shock attenuation varied by footwear condition when subjects ran in minimal footwear and when wearing thicker footwear.

Hypothesis 3: To determine whether running in minimal footwear with less cushioning than subjects are accustomed to requires different kinematic patterns during a prolonged run than when wearing footwear with TTF thicknesses, kinematic dependent variables were calculated over the course of a 30 minute run for three footwear conditions. A 2 way repeated measures ANOVA with footwear condition (thin, medium, and thick) and time (ten footfalls during each five minutes of running) as independent variables was used to compare conditions. Rejecting the null hypothesis indicates subjects utilize different kinematic patterns during a sustained run in minimal footwear compared to thicker footwear.

Hypothesis 4: To determine whether running in minimal footwear with less cushioning than subjects are accustomed to requires alterations to shock attenuation to transfer function relating tibial acceleration and head acceleration were calculated for each time epoch during the 30 minute run for each footwear condition. A 2 way repeated measures ANOVA with footwear condition (thin, medium, and thick) and time (ten footfalls during each five minutes of running) as independent variables was used to compare conditions. Rejecting the null hypothesis indicates subjects utilize different shock attenuation during a sustained run in minimal footwear compared to thicker footwear.

Summary

To investigate how athletes respond to running in footwear considered minimal, three studies were devised. The first study aims to determine if the cushioning properties of footwear are the only factor in altered running patterns on different footwear and surfaces. This study involves running barefoot and shod at 3.0 m/s for six minutes on an aluminum belt treadmill as well as barefoot on a cushioned treadmill belt. Kinematic data, peak accelerations, and a shock attenuation transfer function relating tibial and head accelerations were all used in an attempt to ascertain whether cushioning provided through the running surface (foam belt treadmill) and not footwear will result in running patterns similar to barefoot running (aluminum belt treadmill) or typical shod running on a traditional firm surface (aluminum belt treadmill). If running patterns when barefoot on the cushioned treadmill resemble barefoot running, cushioning is not the only factor affecting how athletes run; however if patterns when barefoot on foam resemble shod running, it is possible that cushioning properties of footwear are heavily related to how athletes run when wearing different footwear.

Footwear used for Study 2 utilized a simple upper, a basic outsole, and varying midsole thicknesses. The midsole thicknesses were: 3 mm heel thickness-3 mm forefoot thickness (thin), 14 mm heel thickness-9 mm forefoot thickness (medium), and 24 mm heel thickness-12 mm forefoot thickness (thick). The footwear were constructed to be identical except for midsole thickness. These three footwear conditions and one barefoot condition were used for Study 2. Subjects were not allowed to see the footwear condition nor walk around in the footwear condition before beginning the treadmill run. Subjects ran a 3.0 m/s for six minutes barefoot on the aluminum belt treadmill, and in the three footwear conditions described above. Dependent variables including kinematics, peak accelerations, a transfer functions related to tibial and head accelerations, and coordination variability were all used to investigate how subjects run from their first step to six minutes in these minimal footwear, and how their running patterns are adjusted to footwear conditions with varying amounts of cushioning.

Study 3 was similar to study 2 in several ways. The same footwear conditions were utilized in study 3 as were used in study 2. Most of the dependent variables used in study 2 were again used in study 3, with the exception of coordination variability. Study

3 focused on reaction to minimal footwear over the course of a sustained run. Subjects visited the lab on three occasions to run at 3.0 m/s for 30 minutes in each shoe described above (thin, medium, and thick).

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CHAPTER IV

CUSHIONING MODE AND MAGNITUDE AFFECT TREADMILL RUNNING PATTERNS

Introduction

Compared to running in typical training footwear (TTF), runners adjust kinematic patterns when barefoot (De Wit, et al., 2000). Barefoot running produces a foot placement at touchdown (TD) that results in less inversion and greater plantar flexion at the ankle joint complex (AJC), in addition to a more vertical leg segment. The knee is more flexed at TD and more extended at midstance. Stance time is also reduced when barefoot (De Wit, et al., 2000; Divert, et al., 2005b; Valiant, 1990). Tibial accelerations increase significantly whereas head acceleration increases slightly (Derrick, et al., 1998; Dufek, Mercer, & Griffin, 2009; Mercer, Bates, et al., 2003; Mercer, et al., 2002; Unold, 1974). Attenuation is often increased when the tibial acceleration increases substantially and the head stays consistent or increases modestly. Therefore, it is likely that barefoot running would also require greater shock attenuation (Derrick, et al., 1998).

The adjustments made when barefoot running was compared to running in TTF could be due to several factors. Cushioning properties of TTF are much different than barefoot. It is likely some adjustments are made due to the loss of underfoot cushioning. Additionally the "geometry of the foot/ground interface" (De Wit, et al., 2000) changes significantly when comparing TTF to barefoot. Most TTF have 10-12 mm of heel lift built into the midsole and potentially more with the insole. This heel lift is a result of the midsole, in the vicinity of the calcaneus, being thicker than the region under the metatarsals. This alters the angle of the foot relative to the ground compared to barefoot.

Another possible factors explaining differences between barefoot and TTF could be constraining the foot within a shoe.

Each of these possibilities has some relative importance to the changes observed when barefoot. Some of the changes measured while barefoot have also been reported when cushioning is reduced with firm footwear implying that cushioning is important. Hennig (1996) reported that subjects adjusted their running style to accommodate greater heel loads in harder footwear; this was accomplished in part by increasing weight bearing in the forefoot. Milani, Hennig, and Lafortune (1997) speculated that when running in less cushioned (harder) footwear, subjects used a less aggressive heel strike pattern in order to protect the body. Not all of this research implicates cushioning as the crucial factor. Although barefoot running has been shown to produce a more flexed knee at TD (De Wit, et al., 2000), a firmer running surface has resulted in greater knee extension at TD (Hardin, et al., 2004). In De Wit's study the barefoot condition contributed less cushioning and produced more knee flexion whereas in Hardin et al.'s study, less cushioning resulted in less flexion. Kerdock (2002) also found slightly greater knee flexion at midstance on a significantly greater stiffness running surface. It is clear that although cushioning might be important in changes made to running patterns, cushioning is not solely driving pattern adjustments.

The extent that heel lift, plantar surface protection, and constraining the foot affect running pattern change is unclear. The change in geometry could affect many aspects of running patterns. During standing, this geometry change would likely affect sagittal plane angles of the foot and the ankle. Given the dynamic nature of running, these changes might also require adaptations further up the kinematic chain.

Substantially reduced plantar surface protection would also require significant changes to running patterns. The plantar surface of the foot is very rich in nerve endings. This combination of factors likely means that pattern changes will be made when protection of the plantar surface is in question. The level of constraint a shoe provides versus barefoot may be dependent on the upper properties of the footwear as well as the fit. A shoe that was very constraining would likely affect relative motion of foot articulations and bones, but the extent this constraint affects more proximal segments and joints is unknown. If the foot could be protected and cushioned without requiring footwear and the change in geometry often accompanying, our knowledge about constraining the foot and altering the foot/ground interfaces geometry may be improved.

The purpose of this experiment was to investigate the effect changing the magnitude of cushioning and the mode of cushioning (i.e. shoe or surface) had on running patterns. It was hypothesized that running patterns will change as a result of cushioning magnitude changes. These changes will include a more horizontal foot at touchdown due to greater plantar flexion and a more vertical leg at contact, more flexion of the knee at midstance, and a reduced stance time. Additionally, it was hypothesized that running barefoot on the cushioned treadmill surface will produce further changes in running patterns when compared to running in normal footwear on a non-cushioned treadmill surface.

Methodology

Subjects

Data from the literature (De Wit, et al., 2000) was used to estimate sample size for a minimum statistical power of 80% with an alpha level of 0.05. Sagittal plane dependant variables utilized in the power analysis included ankle angle, sole angle, leg angle, and the knee angle all at TD. Ten injury free, recreational male runners between the ages of 18 and 55 who used a rearfoot footfall pattern participated in the study. Subjects performed all runs on a Woodway treadmill (Woodway, Waukesha, WI) at 3.0 m/s for 6 minutes in each of five conditions (Figure 5) following a standard treadmill warm up in their own footwear. Between runs, subjects rested until they reported readiness and running conditions were prepared (Hardin, et al., 2004).

Experimental Set-up

Five running conditions were used to manipulate magnitude of cushioning and mode of cushioning (Figure 5). Magnitude of cushioning represents the amount of shock attenuation the condition provides to the runner. Magnitude of cushioning was quantified using an Exeter Research gravity driven impact tester (Exeter Research, Inc., Exeter, NH) and by following ASTM standard F1614-99.2006 (Procedure A). Mode of cushioning represents how this shock attenuation was provided. One mode of cushioning included providing shock attenuation through footwear (two conditions: 18-F & 30-F), and the other mode of cushioning was to apply shock attenuation through the running surface (two conditions: 18-S & 30-S). A final condition required subjects to run barefoot on an un-cushioned running surface. Footwear conditions included a production New Balance 1062 (New Balance Athletic Shoe, Inc., Boston, MA) neutral cushioning TTF with 30 mm of total heel foam and 15 mm of total forefoot foam when both the midsole and the insole were considered (Table 2). The other footwear condition was specifically constructed for the experiment. It utilized a New Balance 790 upper which was a lightweight upper with a very minimal heel counter. The midsole of this footwear was composed of cut and buff ethlylene-vinyl acetate (EVA) with an average hardness of 61 Shore 00. Total heel thickness was 18 mm and total forefoot thickness was 13 mm, again including the midsole and insole. On the bottom of the footwear, the lateral heel and the medial forefoot had a single basic layer of rubber outsole material attached.

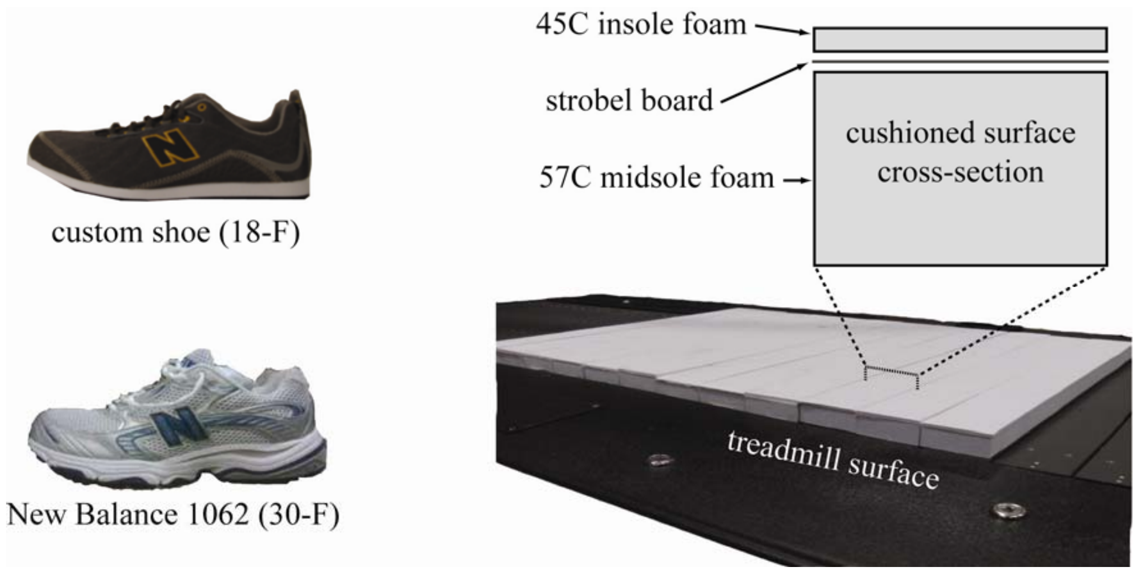

Figure 5. Illustration of footwear conditions and cushioned running surface.

Table 2. Thickness measurements of underfoot layers for footwear conditions and surface conditions. Cushioning properties of conditions were compared using a peak g score. How cushioning was applied is described in the cushioning mode column.

Part thickness and peak g impact score for conditions						
	thickness (mm)					
condition	insole	strobel board	midsole	total	peak g	cushioning mode
barefoot	NA	NA	NA	NA	NA	NA
18-S	5	1	12	18	12.5	surface
18-F	3	1	14	18	15.3	footwear
30-S	5	1	24	30	11.2	surface
30-F	5	1	24	30	10.4	footwear

The two surface conditions allowed subjects to run barefoot on a cushioned treadmill surface. These conditions were created to roughly match cushioning properties of footwear. This surface was achieved by adhering foam slats directly onto the treadmill belt (Figure 5). Both surface conditions consisted of a of 59 Shore 00 durometer foam, glued to a one mm thick strobel material, which was glued to five mm 47 Shore 00 durometer foam. The only difference between the two surface conditions was the thickness of the 59 Shore 00 foam (12 mm and 24 mm). The fifth condition (barefoot) involved running barefoot on the aluminum treadmill belt. Cushioning properties of footwear conditions and surface conditions were compared using peak g score (Table 2) obtained using a gravity driven impact tester and are as follows: 18-S – 12.5 g, 18-F – 15.3 g, 30-S – 11.2 g, 30-F – 10.4 g.

Running kinematics were obtained at 200 Hz using a Qualisys Oqus motion capture system (Oqus 500, Qualisys AB, Gothenburg, Sweden) and acceleration signals were captured at 1000 Hz using Delsys accelerometers (Delsys Incorporated, Boston, Massachusetts). Retro-reflective markers were attached using two sided tape to the subjects left and right greater trochanter, left medial and lateral femoral condyle, left medial and lateral malleolus, and left 1st metatarsal head and 5th metatarsal head. These markers were used as calibration markers within Visual3D (C-Motion, Inc., Germantown, Maryland). Tracking markers were attached via rigid shells to the heel of the footwear (or the skin on the heel), the leg, and the thigh. One accelerometer was attached rigidly to the inferior, antero-medial leg on the left tibia and another attached rigidly to the anterior aspect of the forehead. The accelerometers were attached securely to the skin using 2-sided tape and were further wrapped with athletic pre-wrap to subject tolerance.

A key aspect of this study was subjects having modest information about each footwear/surface condition before running. In order to investigate how subjects adjust from their initial steps in a new shoe or on a new surface to well into a sustained run, subjects were not allowed to walk or run in or on any condition before the test started. To accomplish this, immediately after the test administer put the footwear on the subject, they stood up and boarded the treadmill already moving at 3.0 m/s. If a new surface was attached to the treadmill, subjects were not allowed to walk or run on the surface before the data collection started.

Data Processing

All raw kinematic data were filtered using a dual pass, 2nd order low-pass Butterworth filter with a cut-off frequency of 12 Hz (Hardin, et al., 2004). From kinematic data, local right hand coordinate systems and segment end-points were derived for lower extremity segments. Segment and joint angles were calculated using an Xyz Cardan rotation sequence (Robertson, et al., 2004). For kinematic data, TD was determined using anterior maxima of the heel markers and knee extension maxima were used to determine toe-off (TO) (Fellin & Davis, 2007). Through high speed video analysis, it was determined that the forward maxima of the heel markers were sufficiently close to touchdown for all subjects. Angles were calculated for the foot, leg, and thigh segments and for the AJC and the knee.

Raw acceleration data were low pass filtered using the same Butterworth filter with a cut-off frequency of 50 Hz (Boyer & Nigg, 2007). TD and TO were determined in acceleration signals through visual inspection using recurring spikes in tibial acceleration plots at specific points in time. Each stance phase from acceleration signals had means and linear trends removed (Mercer, et al., 2002). Power spectral densities (PSD) were calculated on these sections using a Fourier Transformation for each subject/condition combination. The ratio of PSD for the head to PSD for the tibia was calculated for each frequency within the range of 0-20 Hz. These ratios were averaged across these frequencies to describe shock attenuation for the data set. Larger ratios indicated more shock attenuation of impact (Derrick, et al., 1998; Mercer, et al.; Shorten & Winslow, 1992).

In order to investigate the effect cushioning magnitude had on dependent variables, a graphical continuum was created. The range of this continuum included barefoot on the firm end of the spectrum and the most cushioned 30-F condition on the soft end. The remaining conditions were placed on the continuum in an appropriate location based on cushioning score. When dependent variables implied the firmer conditions were different than softer conditions, cushioning magnitude was expected to be contributing. The continuum was then utilized to display the differences graphically in an attempt to determine whether consistent transition points were present. The size of the tick mark placed on the continuum explained the strength of the differences. A large tick indicated clear statistical differences isolating conditions to the right and left of the tick location. As an example, if the barefoot condition resulted in significant differences compared to all other conditions, a large tick was placed on the continuum indicating a significant difference between barefoot and the other conditions. If the statistical difference did not clearly differentiate a condition compared to all others, a smaller tick was utilized.

Repeated measures ANOVA was used to determine statistical differences across footwear/surface conditions with a criterion alpha level of 0.05. Dependent variables (DV) included three dimensional angles, peak tibial and head accelerations, and impact attenuation at key instances in time during the support phase. Where group differences were found, a Tukey multiple comparison test was employed to locate the locus of the differences.

Results

Cushioning Magnitude

Magnitude of cushioning had an effect on kinematics at the knee, AJC, and foot as changes were made which seemed to relate to the amount of cushioning provided by the conditions (Table 3). The ankle joint complex (AJC) showed statistically more dorsiflexion for the barefoot condition than the 30-S and 30-F conditions ($p < 0.001$). The 30-F condition was statistically less dorsiflexed than all other conditions except for the 30-S condition ($p < 0.001$). TD sagittal AJC mean values appear to indicate the barefoot condition being isolated in greater dorsiflexion and the 30-F condition being isolated in less dorsiflexion although statistically homogeneous groups were less clear. At TD, the sagittal foot segment exhibited a much flatter landing for the barefoot condition compared to all other conditions ($p = 0.0019$). At TD, the knee was very nearly more flexed for barefoot running compared to all others ($p<0.045$). These were the only kinematic changes observed that implicated the importance of cushioning magnitude.

Table 3. Kinematic data mean values (standard deviation) for each footwear condition as well as probability values from ANOVA averaged across all time epochs. All angles shown are in units of degrees (°) and time in units of seconds (s).

Mean Values (STDEV) for Dependent Variables by Footwear/Surface Condition

	Footwear/Treadmill Condition					
Kinematic Measures	**barefoot**	**18-S**	**18-F**	**30-S**	**30-F**	**P value**
Sagittal AJC at TD	8.18^{c}(5.2)	8.84^{bc}(5.2)	9.07^{cb}(5.2)	9.34^{ab}(5.2)	10.23^{a}(5.2)	<0.001
Sagittal Knee at TD	-10.9^{a}(6.0)	-10.3^{ab}(6.0)	-9.56^{b}(6.0)	-10.3^{ab}(6.0)	-10.3^{ab}(6.0)	0.045
Sagittal Foot at TD	17.5^{b}(7.4)	19.5^{a}(7.4)	19.1^{a}(7.4)	19.3^{a}(7.4)	19.2^{a}(7.4)	0.002
Sagittal Thigh at TD	19.1^{ab}(4.2)	19.5^{a}(4.2)	18.2^{d}(4.2)	18.9^{bc}(4.2)	18.6^{cd}(4.2)	<0.001
Frontal AJC at TD	-7.11^{b}(4.2)	-8.66^{a}(4.2)	-9.26^{a}(4.2)	-8.75^{a}(4.2)	-7.05^{b}(4.2)	<0.001
Sagittal Leg at TD	8.09^{b}(5.1)	9.04^{a}(5.1)	8.55^{b}(5.1)	8.37^{b}(5.1)	8.15^{b}(5.1)	<0.001
Max Knee Flexion	-38.3^{b}(4.9)	-38.4^{b}(4.9)	-37.4^{a}(5.0)	-37.7^{a}(4.9)	-38.6^{b}(4.9)	0.002

Peak AJC Eversion	4.80^{b}(3.3)	4.09^{c}(3.3)	7.04^{a}(3.4)	4.38^{bc}(3.3)	6.62^{a}(3.3)	<0.001
Peak TIR	-5.04^{a}(4.4)	-4.78^{ab}(4.4)	-4.04^{bc}(4.4)	-4.88^{a}(4.4)	-3.45^{c}(4.4)	<0.001
Peak Foot Eversion	-0.43^{b}(3.2)	-1.10^{c}(3.2)	1.42^{a}(3.2)	-0.89^{bc}(3.2)	1.19^{a}(3.2)	<0.001
Stance Time	$.286^{bc}$(.03)	$.288^{ab}$(.03)	$.284^{c}$(.03)	$.288^{ab}$(.03)	$.289^{a}$(0.03)	0.016

Note: Superscripts denote statistically homogenous groups within row statement used.

Stance time also exhibited behavior implicating adjustments made were a result of cushioning magnitude (Table 3). The 18-F condition required less stance time than all other conditions excluding the barefoot condition (p = 0.016). The 30-F condition had a greater stance time compared to both the barefoot and the 18-F condition.

Acceleration signals also favored cushioning magnitude effecting running patterns (Table 4). The thickest footwear condition (30-F) resulted in 7-15% less acceleration than nearly all other conditions (p < 0.001). The barefoot condition resulted in the greatest tibia acceleration. Peak head accelerations for the 30-F condition were at least 10% reduced when compared to all other conditions (p < 0.001). The transfer function indicated attenuation of the acceleration signal in all conditions. The greatest attenuation occurred for the barefoot and the 30-F conditions.

Table 4. Acceleration data mean values (standard deviation) for each footwear condition as well as probability values from ANOVA averaged across all time epochs. Peak acceleration values are in units of gravity (g) while transfer function data are in units of decibels (dB).

Mean Values (STDEV) for Dependent Variables by Footwear/Surface Condition						
	Footwear/Treadmill Condition					
	barefoot	**18-S**	**18-F**	**30-S**	**30-F**	**P value**
Acceleration Measures						
Peak Head Accel	1.75^{a}(0.59)	1.69^{a}(0.59)	1.7^{a}(0.59)	1.71^{a}(0.59)	1.51^{b}(0.59)	<0.001
Peak Tibia Accel	6.75^{a}(1.0)	6.26^{b}(1.0)	6.10^{bc}(1.1)	6.41^{ab}(1.0)	5.87^{b}(1.0)	<0.001
Transfer Function	-7.23^{a}(2.8)	-6.74^{ab}(2.8)	-6.22^{b}(2.8)	-6.37^{b}(2.8)	-7.29^{a}(2.8)	<0.001

Note: Superscripts denote statistically homogenous groups within row statement used.

A graphical representation of the cushioning continuum is shown in Figure 6. All statistical differences were located either between barefoot and all other conditions or between the 30-F condition and all others. Nearly all kinematic differences existed between barefoot and the other conditions. Conversely, nearly all acceleration differences were congregated isolating the 30-S condition compared to the others.

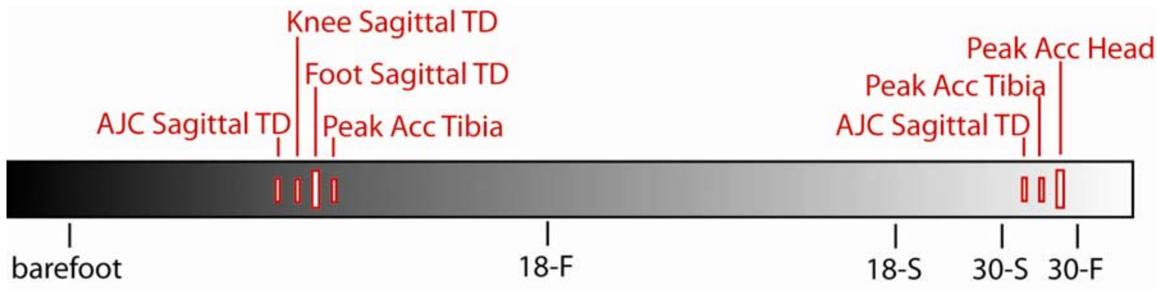

Figure 6. Cushioning continuum displaying conditions and where statistical differences segregate conditions. The darker gradient means less cushioning. Larger ticks designate a clear statistical difference between conditions. Note: not to scale.

Cushioning Mode

The thigh segment angle, eversion variables, and tibial internal rotation (TIR) results indicated the possibility of adaptations to mode of cushioning over magnitude of cushioning. In these dependent variables, footwear conditions clearly separated themselves from the surface and barefoot conditions (Table 3). The thigh segment angle was statistically more vertical for the 18-F condition compared to all others ($p < 0.001$) except the other footwear condition (30-F). The AJC peak eversion angle was greater for footwear conditions compared to all others ($p < 0.001$), as was peak eversion of the foot segment ($p < 0.001$). Peak tibial internal rotation angle was greater for the barefoot and surface conditions compared to all footwear conditions ($p < 0.001$); although the 18-S and 18-F conditions narrowly missed reaching statistical significance (0.056). Although these differences were clear, methodological flaws, which will be discussed in greater detail, may have compromised the eversion variables.

Additional Results

Some kinematic and acceleration measures at the knee, the leg, and the AJC showed adaptations that did not follow expected reactions to cushioning magnitude or cushioning mode. Maximum knee flexion at midstance showed the 18-S and the 30-F to exhibit less flexion compared to all other conditions ($p = 0.0015$). The leg segment was less vertical for the 18-S condition than all others ($p < 0.001$). TD inversion of the AJC was least for the most cushioned 30-F condition and the least cushioned barefoot condition ($p < 0.001$). This pattern was not limited to inversion of the AJC. Shock attenuation also was found to exhibit this behavior as the 30-F and barefoot conditions resulted in more attenuation ($p < 0.001$).

Discussion

One of the purposes of this study was to investigate the effect the magnitude of cushioning had on running patterns. Differences were noted in kinematic and accelerometer parameters suggesting some alterations to running patterns were likely a result of cushioning magnitude differences. These results were accepted as support when conditions providing more cushioning seemed to separate from conditions providing less cushioning along the cushioning continuum. This continuum indicated the difference between barefoot and all others and between 30-F and all others to be important when utilizing sagittal angles at TD and peak acceleration values. There is sufficient evidence to assume some pattern adjustment was likely related to amount of underfoot cushioning.

The other purpose of this study was to investigate whether runners adjust how they run as the mode of cushioning changes. Changes were made to running patterns which resulted in kinematic alterations at the thigh, tibia, AJC, and the foot segment, implying mode of cushioning to be important. The sagittal thigh at TD and peak TIR indicated differences consistent with mode of cushioning affecting running patterns.

Cushioning Magnitude

Cushioning magnitude did not affect kinematics and accelerations similarly (Figure 6). A strong transition point for kinematic data segregated the barefoot condition from all others. The sagittal foot segment at TD isolated the barefoot condition from all others. Similarly, barefoot was also isolated when the sagittal AJC angle at TD was considered. The same was true for the sagittal knee angle at TD. These results agree with De Witt et al.'s (2000) findings on barefoot versus shod running. Clearly barefoot running on a firm surface created alternative kinematic patterns when compared to running with some form of cushioning present.

Peak accelerations favored a point on the continuum isolating the 30-F condition. The tibial data indicated two transitions. One agreed with kinematics data indicating barefoot on a firm surface to require or allow different running patterns than when cushioning was involved. Peak tibial acceleration and peak head acceleration also indicated the thickest footwear condition to reduce acceleration peaks when compared to any other condition. The amount of cushioning was not drastically different between the 30-F condition and the 30-S condition, but peak accelerations were significantly different. It is unclear why this small difference in cushioning magnitude created differences in acceleration. The softest footwear condition may have produced less peak acceleration than the softest surface condition because of the way cushioning was applied (footwear versus surface). While no single point on the continuum separated conditions for all dependent measures, all statistical differences were located at two points on the continuum. The point between barefoot and all others, and the point between the softest footwear and softest surface showed clear differences.

Cushioning Mode

The footwear conditions were isolated from other conditions to some extent when sagittal plane thigh motion and TIR are considered. At the thigh, the 18-F condition was more vertical than all others except the 30-F condition at TD. The tibia showed greater internal rotation for all conditions which aren't footwear, although one comparison was slightly non significant ($p=0.056$). It is important to note the two footwear conditions are very different in terms of cushioning and the treadmill conditions were more similar to the 30-F condition. These results imply wearing footwear resulted in changes to running pattern regardless of cushioning magnitude.

TIR measures provided an interesting finding relative to previous works. Eslami et al. (2007) used running sandals to compare eversion and TIR for shod and barefoot over ground running. No differences were found between groups for eversion or TIR. Peak eversion angles were approximately 11° and TIR angles were about 5°. Stacoff et al. (2000) found similar results using bone pins. Eslami et al. and Stacoff et al. defined TIR as the motion of the tibia relative to the foot. Conversely, we defined the TIR as the motion of the tibia relative to the global coordinate system. The foot segment was likely to be well aligned with the global coordinate system and stationary at midstance where peak TIR was normally measured. Therefore this definition discrepancy was not thought to greatly impact results, and it remains unclear why the footwear conditions in our study tended to limit TIR.

Peak eversion of the AJC and the foot segment being greater for the footwear conditions compared to the surface and barefoot conditions might be related to methodological issues. Stacoff et al. (1992) found attaching markers to the heel counter of footwear potentially over estimates eversion by 2°-3°. This range was very similar to differences noted here for footwear conditions tracked in this manner. There is a strong possibility that some over estimation occurred. Therefore, it is possibly that eversion at the AJC and the foot may not differ across mode of cushioning.

TIR has traditionally been related to eversion with the thought that with greater eversion, more TIR was likely to occur (Hamill, Bates, & Holt, 1992). Even considering the methodological issues relating to eversion, it was unlikely these measurement issues are substantial enough to mask less eversion with footwear as opposed to the greater amounts reported. Interestingly, the thigh was more vertical for the footwear conditions at TD in the sagittal plane. There was a possibility of a top down energy flow where a more vertical thigh segment was driving this internal rotation (Bellchamber & van den Bogert, 2000). If this was the case, this result could be more related to what the footwear required or allowed of the proximal segments than what was required or allowed of the distal segments. Research on proximal to distal versus distal to proximal energy flow is limited; however, these findings may warrant additional research.

Additional Results

The inversion angle at TD did not seem to follow patterns that implicate mode of cushioning nor cushioning magnitude as critical. Valiant (1990) hypothesized an inverted AJC at TD can be a strategy to reduce effective mass. Effective mass can be defined as the portion of the mass that is accelerated (Derrick, et al., 2002). Through joint and segment orientations, effective mass can be modified by a runner and utilized to reduce ground reaction forces when through lack of cushioning, impact forces should increase (B. Nigg, 1986; B. M. Nigg, Bahlsen, Luethi, & Stokes, 1987). Considering these ideas, conditions providing less cushioning require a more inverted foot and less effective mass at TD. Excluding the barefoot condition, results supported this effective mass explanation. The more horizontal foot when barefoot was similar to De Wit, De Clercq, and Aerts (2000) findings. The desire to land with a flatter foot to reduce local underfoot pressures could have prevented an effective mass strategy. De Clercq et al (1994) theorized that the mechanoreceptors in the plantar foot are involved in neuromuscular strategies which are utilized to prevent overloading in the plantar heel. These results are similar to those found for the knee at TD. When no cushioning is present, pressure reduction and overloading avoidance tactics seem to be valued more than impact attenuation through effective mass manipulation.

It was unexpected and was unclear why the most cushioned condition and the least cushioned condition produced the greatest shock attenuation. Increased tibial acceleration peaks when barefoot were expected. Barefoot running resulted in similar peak head accelerations to all other conditions except the most cushioned (30-F). This was not anticipated given where barefoot and the 30-F conditions reside on the cushioning continuum. Acceleration peaks rely solely on time series data, while the shock attenuation calculation utilized here involves the frequency components of time series data. Doing simple ratios of peak tibia acceleration to peak head acceleration in the time domain were also utilized to describe attenuation (Dufek, et al., 2009); this technique provided similar findings to frequency domain attenuation results. Barefoot attenuation was expected, but the large attenuation present in the 30-S conditions was surprising. The peak tibial acceleration for the 30-S condition was less than nearly all other conditions and therefore large attenuation seems unlikely. However, the peak head acceleration for this condition was also significantly less than all others. Therefore, it is possible the attenuation in the barefoot condition was driven by large tibial acceleration and conversely, the small head acceleration was driving the 30-F result.

This study had some limitations. Subjects were not allowed practice time in any of the conditions. We were interested in their reaction to these conditions for the first time. These results may not translate into how patterns would change after sufficient practice. Over the course of the six minute runs, some dependent variables did change with time. Because no interactions were present and to compensate for changes across time, mean data were calculated including data from each minute of the run. It would have also been useful to track the motion of the foot utilizing skin markers as opposed to markers located external to the shoe. Finally, utilizing the forward position of the lateral heel counter marker to locate TD likely created a virtual TD in kinematic data which occurred early for some. This would have affected all kinematic variables at TD. Others have used the vertical position of similar markers to estimate TD with success, although in some instances this was not possible here. De Witt and colleagues (2000) overwhelmingly discovered the differences in kinematics between running barefoot and when wearing TTF to be present at TD and 30 ms before TD. Given these findings, instances where we predict TD in kinematic data slightly early, were not thought to be a concern.

In summary, both mode of cushioning and magnitude of cushioning were found to be important for running pattern changes. Kinematic measures as well as peak accelerations indicated adjustments made to running patterns were related to the amount of underfoot cushioning. Kinematic measures indicated barefoot to be different than all others, and acceleration data indicated the most cushioned footwear condition to be different than all others. Cushioning magnitude is important to changes in running pattern, but other factors are involved. In some instances the most cushioned condition, which was a footwear conditions, resulted in similar behavior to the least cushioned barefoot condition. Footwear also limited tibial internal rotation more than not wearing footwear and altered sagittal thigh kinematics at TD. These results implied wearing footwear affect running patterns regardless of the cushioning shoes provide. More investigation is necessary to fully understand all the factors involved, but our research showed that cushioning magnitude is not the only factor affecting running patterns when footwear or running surface is altered.

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CHAPTER V

RESPONSE AND ACCLIMATION TO TREADMILL RUNNING IN MINIMAL FOOTWEAR

Introduction

Minimal running shoe sales have encountered rapid growth over the last several years and many product offerings are currently on the market from a variety of manufactures. Minimal footwear, according to the footwear industry, can be defined as a shoe with a thin, flexible midsole and outsole and a light, basic upper with little or no heel counter. These shoes are typically built with little underfoot material to cushion impacts and protect the foot from environmental factors. Many examples with very diverse amounts of underfoot material are currently in the market. Just a few of the current products include: Vibram's Fivefingers (Vibram USA, Concord, MA), Nike Free (Nike Inc., Beaverton, OR), New Balance Minimus (New Balance Running Shoe, Inc., Boston, MA), and Terra Plana "Vivo' (Terra Plana International, London, United Kingdom). Research on how runners react to wearing these footwear is limited.

Squadrone and Gallozzi (2009) used an instrumented treadmill and employed experienced barefoot runners to investigate a minimal shoe. Subjects were given a pair of Vibram Fivefingers and a pair of typical training footwear (TTF) ten days before their data collection to become accustomed to the footwear conditions. Subjects ran for six minutes barefoot, with the Vibram Fivefingers, and with TTF. The Vibram Fivefingers resulted in kinematics of the leg and foot which were more similar to barefoot than TTF. For example, the foot was significantly more plantar flexed for the Fivefingers compared to the TTF condition at touchdown (TD). Impact forces were also reduced with the

Fivefingers shoe likely as a result of kinematic alterations made to shorten stride length and increase stride frequency. Contact times when barefoot and when wearing the Fivefingers were similar (and less than shod), but flight times were greater for the Fivefingers. These authors speculate the differences in flight times between the Fivefingers and barefoot runs might be due to the minute protection the Fivefingers does provide. This protection may be enough to accomplish a more vigorous push off compared to barefoot.

Although there is a lack of experimental research on running in minimal footwear, if kinematic differences are similar to barefoot versus TTF as Squadrone and Gallozzi (2009) found, much more literature can be used to theorize how running in minimal footwear might change. De Wit et al. (2000) found a much more horizontal foot placement at TD when comparing barefoot to shod. This result was due to greater plantar flexion as well as a more vertical leg at contact. This vertical leg position was obtained through knee flexion as the thigh orientation was similar between the two conditions. During initial ground contact, Clarke et al. (1983) found the knee in shod running goes from more extended to more flexed than in barefoot running. This more flexed position during shod running continues throughout midstance. At the ankle joint complex (AJC), barefoot runners landed more neutral than shod runners who landed more inverted. Eslami et al. (2007) had subjects run (controlled at 170 steps per minute) across a forceplate barefoot and in running sandals while collecting kinematic data using skin mounted markers. They found insignificant differences in rearfoot and tibial motion when running shod was compared to running barefoot. Unold (1974) found that while running barefoot, tibial accelerations were greater than when wearing shoes. Kurz and

Stergiou (2003) used spanning set methodology to show that barefoot running produced greater variability in sagittal knee and ankle joint motion than running in hard or soft footwear. Considering Squadron and Gallozzi's findings, one might assume that the majority of these differences between barefoot and shod running might also occur when minimal footwear are worn.

For runners accustomed to training in TTF, a minimal shoe would likely provide very different cushioning and sensations. Runners already accustomed to training barefoot have likely adopted kinematic patterns sufficient for very little or no underfoot cushioning or protection. Their tissues, including lower extremity musculature and plantar foot surface skin, may have adapted to allow for safe and efficient movement patterns when running barefoot. For these individuals, running in something minimal is probably not an extremely novel task. Conversely, for those who typically wear very protective and cushioned TTF, running in minimal footwear with very little underfoot material is likely more of a novelty. Ferris et al., (1999) found runners adjusted leg stiffness very accurately and quickly as they ran down a runway with a particular surface stiffness to a forceplate with a different surface stiffness. Runners made adjustments within a single step onto the new surface. These runners were given ample practice time in order to get accustomed to the differences in stiffness of the forceplate. The majority of footwear studies allow ample practice time in experimental footwear before data are captured; however, it is likely that many consumers buy new footwear and go for a run. We do not know how runners will respond to running in minimal footwear for the first time. For many, running in very minimal footwear will be a novel task which requires exploration and learning. Similar to the runners in Ferris et al. (1999), who were allowed practice time, these individuals might require many steps in order to discover a suitable kinematic pattern.

The purpose of this study was to investigate if running patterns were adjusted while running in minimal footwear for the first time and the time it takes for these adjustments to occur. It was hypothesized that runners would alter running patterns based on footwear conditions resulting in changes consistent with the research discussed on barefoot and minimal footwear. Predicted kinematic changes included a more horizontal foot at touchdown, more flexion of the knee at midstance, and a reduced stance time. Peak accelerations were expected to be increased with less material underfoot, and barefoot and minimal conditions were expected to produce more variability in movement patterns. Secondly, it was hypothesized that changes made due to footwear will occur relatively quickly, but not in one step as shown with practice.

Methodology

Subjects

Data from the literature was used to estimate sample size for a minimum statistical power of 80% with an alpha level of 0.05 (De Wit, et al., 2000). Sagittal plane dependant variables utilized in the power analysis included ankle angle, sole angle, leg angle, and the knee angle all at TD. For this reason, ten injury free, recreational male runners between the ages of 18 and 55 who used a rearfoot footfall pattern participated in the study. Subjects performed all runs on a motorized Woodway treadmill (Woodway, Waukesha, WI) at 3.0 m/s for 6 minutes in each of four conditions (Figure 7) following a standard treadmill warm up in their own footwear. Between runs subjects changed footwear and rested until they reported readiness (Hardin, et al., 2004).

Experimental Set-up

Three pairs of specifically constructed shoes were used in this study (Figure 7). All shoes utilized a New Balance 790 upper, a lightweight upper with a very minimal heel counter. The midsole of this footwear was composed of cut and buff ethlylene-vinyl acetate (EVA) with an average hardness of 61 Shore 00. Each of the three pairs of shoes had distinctly different EVA thicknesses (Figure 7). One shoe had a typical TTF thickness (12 mm forefoot midsole and 24 mm rearfoot midsole foam, one simulated a very minimal, barefoot inspired shoe, and one fell between the previous two midsole dimensions. On the bottom of the footwear, the lateral heel and the medial forefoot had a single basic layer of rubber outsole material attached. Cushioning properties of footwear conditions were compared using a peak g score obtained using a gravity driven impact tester and were as follows: thick – 14.3 g, medium – 16.8 g, thin – 40.1 (Exeter Research, Inc., Exeter, NH).

Figure 7. Footwear conditions utilized in the study. Foam thicknesses (mm) and peak g impact scores are presented.

Running kinematics were obtained at 200 Hz using a Qualisys Oqus motion capture system (Oqus 500, Qualisys AB, Gothenburg, Sweden) and acceleration signals were captured at 1000 Hz using Delsys accelerometers (Delsys Incorporated, Boston, Massachusetts). Retro-reflective markers were attached using two sided tape to the subjects left and right greater trochanter, left medial and lateral femoral condyle, left medial and lateral malleolus, and left 1st metatarsal head and 5th metatarsal head. These markers were used as calibration markers within Visual3D (C-Motion, Inc., Germantown, Maryland). Tracking markers were attached via rigid shells to the heel of the footwear (or the skin on the heel), the leg, and the thigh. One accelerometer was attached rigidly to the inferior, antero-medial leg on the left tibia and another attached rigidly to the anterior aspect of the forehead. The accelerometers were attached securely to the skin using 2-sided tape and were further wrapped with athletic pre-wrap to subject tolerance.

A key aspect of this study was subjects having modest information about each footwear condition before running. In order to investigate how subjects adjust from their first step in a new shoe, subjects were not allowed to walk or run in any condition before mounting the moving treadmill. To do this, after the test administrator put the footwear on the subject, the subject stood up, placed his left foot on the side of the treadmill and used his right foot to gauge the speed of the moving treadmill before starting to run. This procedure ensured subjects had as little information as possible before beginning to run.

Data Processing

All raw kinematic data were filtered using a dual pass, 2nd order low-pass Butterworth filter with a cut-off frequency of 12 Hz (Hardin, et al., 2004). From kinematic data, local right hand coordinate systems and segment end-points were derived for lower extremity segments. Segment and joint angles were calculated using an Xyz Cardan rotation sequence (Robertson, et al., 2004). For kinematic data, TD was determined using anterior maxima of the heel markers and knee extension maxima were used to determine toe-off (TO) (Fellin & Davis, 2007). Through high speed video analysis, it was determined that the forward maxima of the heel markers were sufficiently close to touchdown for all subjects. 3D angles were calculated for the foot, leg, and thigh segments and for the AJC and the knee.

Raw acceleration data were low pass filtered using the same Butterworth filter with a cut-off frequency of 50 Hz (Boyer & Nigg, 2007). TD and TO were determined in acceleration signals through visual inspection using recurring spikes in tibial acceleration plots at these points in time. Each stance phase from acceleration signals had means and linear trends removed (Mercer, et al., 2002). Power spectral densities (PSD) were calculated on these sections using a Fourier Transformation for each subject/condition combination. The ratio of PSD for the head to PSD for the tibia was calculated for each frequency within the range of 0-20 Hz. These ratios were averaged across these frequencies to describe shock attenuation for the data set. Larger ratios indicated greater impact shock attenuation (Derrick, et al., 1998; Mercer, et al., 2002; Shorten & Winslow, 1992).

In order to evaluate coordination variability, continuous relative phase (CRP) was employed. Position and angular velocities of the foot, leg, and thigh were used to create phase planes which were each normalized to a unit circle to account for amplitude and frequency differences between segments (Hamill, et al., 1999). Arctangent was then utilized to compute phase angles based on the normalized position and angular velocity time series. In order to investigate the relationship between the thigh and tibial internal rotation and the foot and tibial internal rotation, three coupling comparisons were utilized: thigh flexion/extension and tibial rotation ($Th_{F/E}$-Tib_{Rot} – Comparison A), thigh abduction/adduction and tibial rotation ($Th_{Ab/Ad}$-Tib_{Rot} – Comparison B) and tibial rotation and foot eversion/inversion (Tib_{Rot}-$Ft_{Ev/In}$ – Comparison C) (Hamill, et al., 1999). To further investigate sagital plane coordination and the influence of the amount of underfoot cushioning, intralimb couplings for left thigh-left leg (Comparison D) and left leg-left foot (Comparison E) were also calculated (Seay, et al., 2006). All comparisons utilized a proximal minus distal segment convention. Finally, absolute values were used resulting in a CRP measure between 0 and 180° to avoid phase discontinuities. CRP variability was calculated for each subject by condition at each time epoch using stride-to-stride standard deviations in CRP.

To test for a main effect for time, time epochs were created utilizing ten steps for each minute on the treadmill. Because runners boarded a moving treadmill, the initial steps on the treadmill were often unnatural. Utilizing acceleration traces, the first step that appeared qualitatively similar to steps farther into the run was utilized as the initial step in the analysis. This step was also defined as the first in kinematic data. Typically one or two steps immediately following getting onto the treadmill were not included in the analysis. Ten steps immediately following the defined first step were used to create time epoch 1. Ten steps at the beginning of each subsequent minute on the treadmill were utilized to create remaining time epochs.

To look more closely at the initial time on the treadmill, a moving window analysis was utilized to investigate if standard deviations were reduced over the first 20 steps on the treadmill. A five point moving window was utilized to calculate average standard deviations of acceleration dependent variables (DVs) over five step increments. Steps one through five made up the first moving window. Steps two through six made up the second. This trend continued with steps 15 to 20 making up the final window. The average standard deviations for these windows were compared to determine if the variability of acceleration signals changed over the course of the initial 20 steps on the treadmill. This would indicate a stabilization of movement patterns.

Repeated measures ANOVA was used to determine statistical differences ($p < .05$) for footwear conditions and time. DVs consisted of three dimensional angles, peak accelerations, impact attenuation and coordination variability. Where group differences were found, a Tukey multiple comparison test was employed to locate the locus of the differences.

<u>Results</u>

No significant Footwear Condition × Time interaction was present study wide for any dependant variables. Thus, all time points were averaged when comparing footwear conditions and all footwear conditions were averaged when investigating time related differences.

Effect of Footwear Condition

In general, the amount of underfoot material had an effect on many kinematic variables (Table 5). Sagittal plane angles at TD of the AJC joint and the foot segment were both significantly greater for the medium and thick conditions compared to the barefoot and thin conditions ($p < 0.001$ & $p < 0.001$). The leg segment was significantly more vertical in the sagittal plane at TD for the barefoot and thin condition compared to the thick condition ($p < 0.001$). In the frontal plane, the foot was significantly more flat at TD for the barefoot condition compared to the thin and thick conditions and, although not statistically significant, was also almost 9% flatter than the medium condition ($p = 0.08$). When the frontal ACJ is considered at TD, the barefoot condition was significantly flatter than all other conditions ($p = 0.006$). Peak eversion was greater for all footwear conditions than it was for the barefoot condition ($p < 0.001$). Following TD, stance time was significantly greater as the amount of underfoot material increased. Stance time increased from barefoot to the thin condition and from the thin condition to both the medium and thick conditions ($p < 0.001$). All of these data as well as probability values are shown in Table 5.

Table 5. Kinematic mean values (standard deviation) for each footwear condition as well as probability values from ANOVA averaged across all time epochs. All angles shown are in units of degrees (°) and time in units of seconds (s).

Mean Values (STDEV) for Dependent Variables by Footwear Condition

	Footwear Condition				
Kinematic Measures	**Barefoot**	**Thin**	**Medium**	**Thick**	**P value**
Sagittal AJC at TD	8.91^{b}(2.9)	7.93^{b}(2.8)	10.40^{a}(2.8)	10.9^{a}(2.9)	<0.001
Sagittal Knee at TD	-7.18^{a}(4.1)	-6.06^{bc}(4.1)	-6.90^{ab}(4.1)	-5.60^{c}(4.1)	<0.001
Sagittal Foot at TD	20.6^{b}(3.4)	20.0^{b}(3.3)	22.6^{a}(3.3)	23.4^{a}(3.5)	<0.001
Frontal AJC at TD	-6.96^{b}(3.0)	-8.02^{a}(3.0)	-7.91^{a}(3.0)	-8.25^{a}(3.0)	0.006
Frontal Foot at TD	-8.55^{b}(2.6)	-9.69^{a}(2.6)	-9.31^{ab}(2.6)	-9.67^{a}(2.6)	0.008
Sagittal Leg at TD	11.1^{b}(2.7)	11.1^{b}(2.7)	11.4^{ab}(2.7)	11.9^{a}(2.7)	<0.001
Sagittal Thigh at TD	18.3^{a}(1.5)	17.4^{b}(1.5)	18.5^{a}(1.5)	17.7^{b}(1.5)	<0.001
Peak AJC Eversion	3.38^{b}(2.3)	8.49^{a}(2.3)	8.43^{a}(2.3)	8.29^{a}(2.3)	<0.001
Peak TIR	-6.51^{a}(3.4)	-4.81^{b}(3.3)	-4.48^{b}(3.3)	-6.16^{a}(3.3)	0.002
Max Knee Flexion	-35.5^{b}(4.7)	-35.3^{b}(4.7)	-37.2^{a}(4.7)	-35.8^{b}(4.7)	<0.001
Stance Time	$.285^{c}$(0.03)	$.290^{b}$(0.03)	$.293^{a}$(0.03)	$.296^{a}$(0.03)	<0.001

Note: Superscript denotes statistically homogenous groups within row statement used.

Acceleration related DVs predominantly increased as footwear became minimal and conversely, coordination variability was greater when barefoot compared to when the thin condition was worn (Table 6). Peak acceleration values were least at the leg and head for the thickest midsole condition. The transfer function describing signal attenuation failed to reach statistical significance across the footwear conditions. The barefoot condition showed statistically greater variability than the thin condition for comparison A ($p = 0.049$), comparison B ($p = 0.19$), and comparison C ($p < 0.001$).

Table 6. Acceleration and coordination variability mean values (standard deviation) for each footwear condition as well as probability values from ANOVA averaged across each time epoch. Peak acceleration values are in units of gravity (g), transfer function data are in units of decibels (dB) and CRP variability are in units of degrees (°). CRP Variability Comparisons are as follows: $Th_{F/E}$-Tib_{Rot} – Comparison A, $Th_{Ab/Ad}$-Tib_{Rot} – Comparison B, Tib_{Rot}-$Ft_{Ev/In}$ – Comparison C, $Th_{F/E}$-$Tib_{F/E}$– Comparison D, $Tib_{F/E}$-$Ft_{F/E}$– Comparison E.

Mean Values (STDEV) for Dependent Variables by Footwear Condition

	Footwear Condition				
	Barefoot	**Thin**	**Medium**	**Thick**	**P value**
Acceleration Measures					
Tibial Peak Acceleration	5.60^{a}(1.5)	5.57^{a}(1.5)	5.17^{b}(1.5)	4.57^{c}(1.5)	<0.001
Head Peak Acceleration	1.22^{ab}(0.33)	1.26^{a}(0.33)	1.25^{a}(0.33)	1.15^{b}(0.33)	0.008
Transfer Function	-8.94(1.9)	-9.17(1.9)	-9.31(1.9)	-8.94(1.9)	0.16
Coordination Variability					
CRP Variability Comp A	11.6^{a}(4.4)	10.2^{b}(4.4)	10.8^{ab}(4.4)	11.0^{ab}(4.4)	0.049
CRP Variability Comp B	27.2^{a}(10)	23.4^{b}(10)	25.1^{ab}(10)	26.1^{ab}(10)	0.019
CRP Variability Comp C	18.0^{a}(4.9)	14.5^{b}(4.9)	14.9^{b}(4.9)	15.8^{b}(4.9)	<0.001
CRP Variability Comp D	3.66^{a}(0.78)	3.29^{ab}(0.77)	3.19^{bc}(0.77)	2.88^{c}(0.77)	<0.001
CRP Variability Comp E	7.64(6.3)	7.62(6.3)	7.52(6.3)	7.48(6.3)	0.99

Note: Superscript denotes statistically homogenous groups within row statement used.

Effect of Time

Changes were made over the course of the run for several kinematic DVs indicating some adjustments were made rapidly, while others were made more gradually (Figure 8). The sagittal plane knee angle and the sagittal plane thigh angle at TD showed rapid changes as statistical differences indicated the initial ten steps on the treadmill were significantly different than all time epochs later in the run ($p = 0.04$ & $p < 0.001$). Three other kinematic variables indicated the first ten steps to be significantly different, or nearly statistically different than epoch 2, while also exhibiting continued changes later in the run. Maximum knee flexion at midstance was statistically less during the initial ten steps than all epochs after minute two (p = 0.029). Mean data indicated epoch 1 showed less flexion than epoch 2 but significance was not reached. Peak eversion for the initial ten steps was less than at all other time epochs while epoch 2 showed less eversion than the final epoch (p < 0.001). Conversely, stance time indicated the initial ten steps to be significantly less than epoch 2 which was significantly less than all other time epochs (p < 0.001).

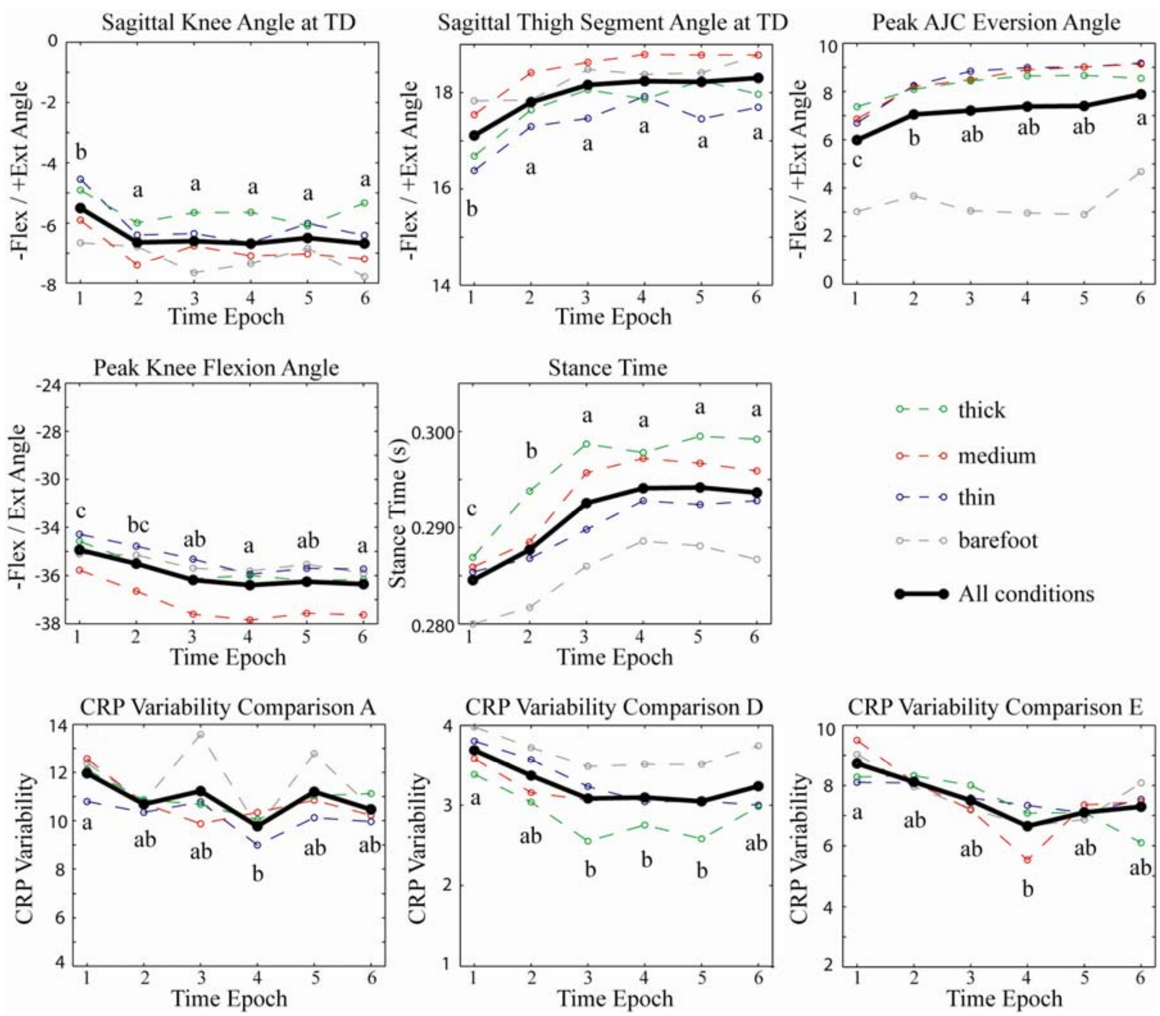

Figure 8. Plots of mean values for significant main effects of time as well as individual footwear condition plots. Statistical differences only apply to mean values which are averaged across all footwear conditions. Superscript denotes statistically homogenous

groups within plot statement used. CRP Variability Comparisons are as follows: $Th_{F/E}$-Tib_{Rot} – Comparison A, $Th_{F/E}$-$Tib_{F/E}$– Comparison D, $Tib_{F/E}$-$Ft_{F/E}$– Comparison E.

Three coordination variability comparisons showed epoch 4 to exhibit significantly less variability than epoch 1 (Figure 8). The comparison between thigh flexion/extension and tibial rotation (comparison A) resulted in significantly less variability at the beginning of four minutes than the initial ten steps in the run ($p = 0.017$). Flexion/extension of the thigh versus the tibia (comparison D) showed minutes three through five to be less variable than the initial ten steps ($p = 0.003$). Finally, flexion/extension of the tibia relative to the foot (comparison E) resulted in less variability at the beginning of four minutes than the initial steps on the treadmill ($p = 0.031$). Unlike the coordination related dependant variables, acceleration dependant variables did not show any main effects when comparing these time epochs.

Analyzing standard deviations utilizing the five point moving window on peak acceleration data provided support for changes occurring rapidly (Figure 9). Peak head acceleration showed the first window, which included steps one through five (window 3), to have significantly greater average standard deviation than windows six through 13 and windows 17 and 18 ($p = 0.001$). Significant differences in peak tibial acceleration were less frequent, but the same trend was present as the first window tended to show more variation than several windows later in the run ($p = 0.002$).

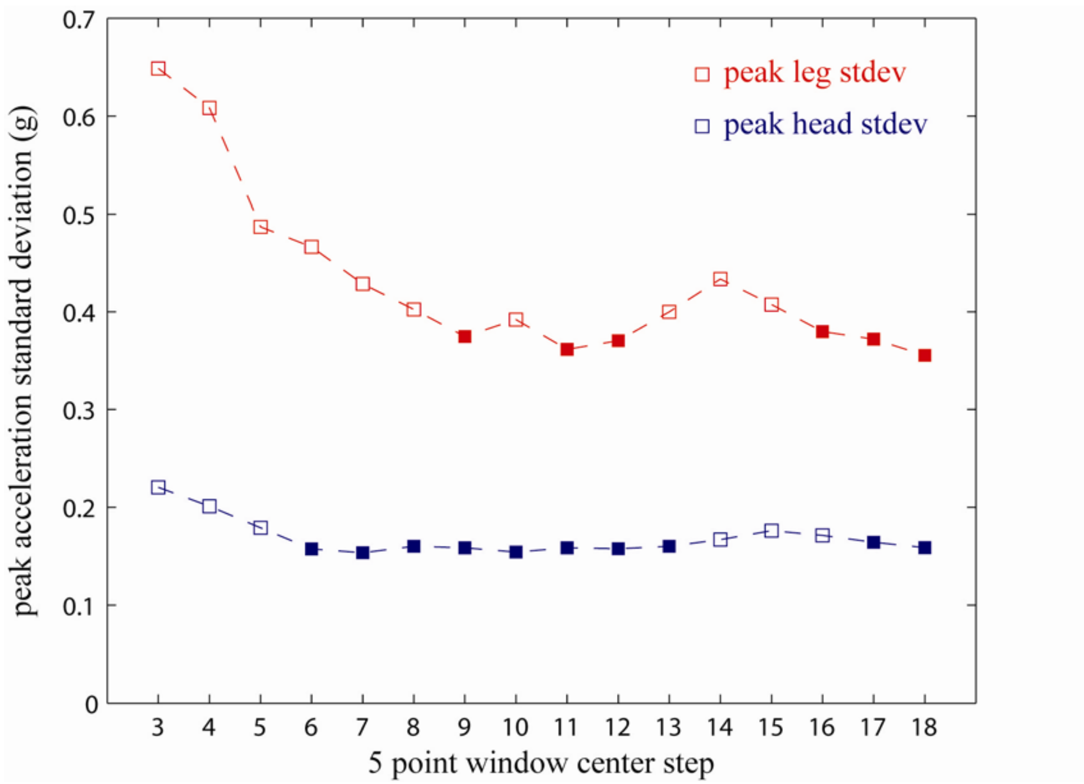

Figure 9. Peak leg and head five step moving window averages of standard deviations averaged across all footwear conditions. Solid square boxes indicate reduced variability compared to the initial window centered on step 3.

Discussion

The purpose of this study was to investigate if running patterns were adjusted while running in minimal footwear for the first time and the time it takes for these adjustments to occur. As hypothesized, runners made adjustments to running patterns which were predominantly expected in minimal conditions (barefoot and thin). Segment and joint angles at TD including foot, AJC, and leg showed statistical differences consistent with adaptations made due to less cushioning or protection. Peak accelerations at the leg and head were increased when underfoot material was reduced. Finally, although most coordination variability comparisons implicated barefoot running showed the most variability and the thin condition to produce the least, the sagittal plane coordination of the leg and thigh produced increased variability as underfoot material was reduced. These results indicated adjustments made to running patterns were related to the amount of underfoot material.

The second hypothesis was correct as changes occurred relatively quickly; however, changes continued well into the run. Some kinematic dependent variables indicated the first ten steps to be different than the ten steps taken a minute into the run. The steps at epoch one were often quite different than the more consistent steps throughout the rest of the run. Statistical differences were noted between epoch 1 and epoch 2 for knee flexion angle, the sagittal thigh segment angle at TD as well as for peak AJC eversion and stance time. Statistical differences were also noted between epoch 2 and epochs later in the run for maximum knee flexion, peak eversion, and stance time. Three coordination variability comparisons tended to show epoch 1 to be significantly more variable than epoch 4, indicating adjustments continuing well into the run.

Moving window analysis of peak acceleration standard deviations across the initial twenty steps on the treadmill also showed adaptations occurred rapidly. It was expected that large standard deviations would be present very early in the run and standard deviations would be reduced when the trial and error of attempting to discover a suitable pattern was reduced. These data indicated that initial adaptations to running in the footwear conditions occurred very quickly.

Effect of Footwear Condition

Sagittal plane kinematic adjustments made as a result of reduced underfoot material and cushioning agreed with previous works comparing barefoot to typical shod running and minimal footwear to TTF. De Wit et al. (2000) found barefoot running to produce a more vertical leg segment and a flatter foot placement at TD when comparing barefoot running to shod running. In this study, the sagittal AJC angle at TD exhibited greater dorsiflexion for the thick and medium conditions compared to the others as did the foot segment angle indicating similar adjustments. Also in agreement, the leg segment was more vertical when the barefoot or thin conditions were compared to the thick condition. Stance time was greater for the thick condition compared to the barefoot condition as was found by Divert et al. (2005b) for barefoot versus shod running. Further, Squadrone and Gallozzi (2009) showed increased stride frequency when comparing the Vibram five-fingers to typical training footwear. In agreement, our study found the thin condition had greater stance time than the barefoot condition, but reduced stance time compared to the medium or thick conditions. The thin condition should provide similar cushioning to the Vibram shoe used in the Squadron and Gallozzi experiment. Sagittal plane kinematic adaptations made due to wearing footwear with less cushioning properties via less underfoot material were consistent with previous works comparing barefoot to typical shod running, and minimal footwear to typical training footwear.

Our results showed the amount of underfoot material may not contribute to the amount of eversion (pronation) allowed or necessitated by a shoe. Greater peak eversion of the AJC and the foot segment for the footwear conditions compared to the barefoot condition might have been in part related to methodological issues. Stacoff, Reinschmidt, and Stussi (1992) found attaching markers to the heel counter of footwear to potentially over estimate eversion by 2-3°. This range would not entirely explain the differences noted here for footwear conditions which were also tracked in this manner, but may explain a portion of these differences. Cavanagh (1981) stated that footwear with firmer, wider midsoles should be better at controlling eversion (pronation) than footwear with softer, narrower midsoles. In the present experiment, each midsole had similar hardness characteristics; however, the width of the midsole under the heel were different due to the midsole thickness differences. The thin condition had a midsole which was 6.6 cm at the widest part of the rearfoot, the medium shoe was 7.5 cm, and the thick was 8.2 cm. Hamill et al. (1988) found a racing flat to show greater eversion than a training shoe. The racing flat had a narrower heel base which may have contributed to the increased rearfoot motion. Clarke et al. (1983a) showed greater rearfoot motion when footwear without heel flares were compared to those with heel flares. The thin shoe in our study had no heel flare, but the medium condition had somewhat of a flare, and the thick condition had the largest flare. The results of the current study did not support this previous research. Even though these footwear conditions were very different in terms of thickness, width, and heel flare, no eversion differences were noted between the footwear conditions.

As hypothesized, greater peak tibial acceleration values were present for footwear with less underfoot material. These results agree with Unold (1974) who found greater peak accelerations at the leg for barefoot running compared to shod. Hardin and Hamill (2002) similarly found greater midsole hardness to produce greater tibial accelerations for downhill running. These results imply less force when more underfoot material is present, because runners are able to make adjustments as has been shown previously (Clarke, Frederick, & Cooper, 1983; Hardin, et al., 2004). Given the heavy involvement of the hip, knee, and ankle at TD in running, the mass accelerated at impact can change.

The ability of joints to effect the ground reaction force has been termed effective mass, and can be simply defined as the portion of the mass that is accelerated (Derrick, et al., 2002). As the knee becomes more flexed, effective mass would be reduced making the leg segment easier to accelerate and the impact force may not be increased. The barefoot condition showed greater knee flexion at TD compared to the thin and thick conditions. Therefore the more flexed knee at TD in the barefoot condition compared to the thin condition may help explain the reduced peak acceleration at the head when barefoot compared to the thin condition. The reduced head acceleration for the thick condition can be explained because midsole cushioning helps to reduce impact acceleration at the tibia and the head. Therefore it seemed like effective mass manipulation might have been utilized in the barefoot condition to help mitigate potentially large accelerations traveling up the kinematic chain; however, this was not shown for the thin condition. Even though the thin condition was very minimal and provided little cushioning, it seemed to affect running patterns enough to exhibit some differences compared to the barefoot condition.

Alterations made at the AJC are thought to contribute to effective mass as well. A more inverted AJC at touchdown would reduce effective mass (Valiant, 1990). Since each footwear condition produced a more inverted AJC compared to barefoot, effective mass would tend to be less in footwear conditions. It was expected that if effective mass was manipulated, it would be reduced for the more minimal conditions. This certainly was not the case when looking at these frontal plane AJC angles. Each of the footwear conditions probably felt firmer underfoot than typical training footwear given the impact scores were greater than what typical training footwear would produce. Therefore a more inverted AJC might have indeed been an effective mass manipulation. For the barefoot condition, the desire to reduce local pressures underfoot may have been more important than impact shock attenuation and a flatter foot placement was utilized. De Clercq et al (1994) theorized that the mechanoreceptors in the plantar foot are involved in neuromuscular strategies which are utilized to prevent overloading in the plantar heel. When no cushioning is present, pressure reduction and overloading avoidance tactics seem to be valued more than impact attenuation through effective mass manipulation.

The barefoot condition tended to show greater CRP variability than all other footwear conditions. This is in agreement to Kurz and Stergiou (2003) findings utilizing spanning sets described earlier. Running on this particular treadmill barefoot provided unique proprioceptive experience as the aluminum slats are gapped slightly and these gaps change shape as the belt moves. These sensations may have produced coordination patterns that were more variable. This variability may have been due to searching for suitable running kinematics which satisfied overloading reduction and the response to the unique underfoot feel. When running barefoot on trails and roads, the same strategies and issues are likely to exist. The treadmill was a clean, smooth surface compared to most outdoor running routes, which may explain why the thin condition showed no increased CRP variability compared to the other footwear conditions. It is anticipated that difference may be present if this study was recreated on an outdoor surface which had greater environmental dangers making the lack of protection offered from the thin conditions more relevant.

Effect of Time

Ferris et al., (1999) found nearly instantaneous adjustments were made when a known surface change was entertained by a runner; however, our data indicated some changes occurred quickly but not instantaneously when an unknown footwear condition was worn during a treadmill run. Ferris et al.'s subjects had ample practice time to learn what running pattern was applicable to the run, and what adjustments were necessary for running on the new surface. In our study subjects had very little information and no practice time in the footwear conditions. Without any prior knowledge of the cushioning properties of the footwear, or the kinematic pattern the footwear condition requires, it would be difficult for runners to adjust instantaneously. We did show changes occurred quickly however. Several kinematic variables indicated the first ten steps to be significantly different than those one minute into the run. In fact, the majority of differences in many dependant variables were already observed when focusing on the initial ten steps on the treadmill. If only data from the these initial ten steps were utilized to investigate effects of footwear condition, similar results were found to utilizing all time epochs, although statistical significance wasn't always reached. The same was true for peak acceleration values. These results are interesting considering kinematic changes are still occurring well into the run. It is clear that the substantial changes made due to footwear condition occurred very quickly.

The moving window analysis, used on acceleration standard deviation data, showed variability was reduced early in the run. Even though subjects are essentially jumping onto a moving treadmill wearing footwear they know very little about, they may have settled into a pattern which displayed reduced variability of acceleration signals after about only six treadmill steps. If the large changes due to footwear differences are occurring very early, the larger early standard deviation windows might be showing these adjustments taking place. Peak head acceleration data showed the first moving window centered at step three to show greater variability than the window centered on step six. As previously mentioned, one or two steps were often eliminated due to defining step one as the first step qualitatively similar to steps farther into the run. Therefore the number of actual steps on the treadmill might be seven or eight before standard deviations are significantly reduced for peak head accelerations. Peak tibial acceleration did not result in significant differences until a couple steps later but Figure 9 shows very similar trends. Therefore it appears as though a somewhat repeatable pattern with relatively low variability was possible for very unique footwear after only seven or eight steps even though runners began by jumping onto a moving treadmill. This reduction in standard deviations might have been a result of initial changes made very early in the run due to the footwear conditions.

Kinematic changes later in the run may have implied subjects began the run conservatively. At epoch 1 the thigh was more vertical in the sagittal plane and stance time was less than at epoch 2. After this initial epoch the thigh segment became less vertical and stance times increased. A less vertical thigh might be utilized to increase stride length, resulting in increased stance time and likely increased impact forces (Hamill, Derrick, & Holt, 1995; Mercer, et al., 2002). Stance time continued to increase and did not stabilize until epoch 3. Peak eversion and peak knee flexion also did not stabilize until later in the run and may have been a result of these longer, more aggressive strides (Clarke, Frederick, & Hamill, 1983b; Derrick, et al., 1998). It is possible that as subjects became more comfortable with the footwear conditions over the course of several minutes, they fell into their normal running pattern. If they began the run conservatively due to unknown footwear characteristics, moving towards something that was normal or natural for them as they became confident and comfortable would not be unexpected. This explanation may also relate to the coordination variability findings. Coordination variability implicated coordination in the middle of the run to be more consistent than earlier in the run. Three CRP comparisons resulted in significantly greater variability for epoch 1 compared to epoch 4. One of these comparisons also indicated less variability for epochs 3 and 5 compared to epoch 1. It is possible that it took runners this long to get into a repeatable, comfortable, and aggressive running pattern.

It is also unclear why coordination variability often increased late in the run. Subjects were not aware of exact stopping times, but they did know the runs would last about six minutes. Because the treadmill was started prior to the runners boarding, the clock on the treadmill indicated six minutes before the data collection ended. It is possible that subjects lost some focus late in the runs as they anticipated a stop command.

This study had some limitations. Subjects were not allowed practice time in any of the conditions. We were interested in their reaction to these conditions for the first time. These results may not translate into how footwear might change patterns after sufficient practice. Over the course of the six minute runs, some dependent variables did change over time which might have resulted from learning.

Finally, utilizing the forward position of the lateral heel counter marker to locate TD likely created a virtual TD in kinematic data which occurred early for some subjects. This would have affected many kinematic variables at TD. Others have successfully used the vertical position of similar markers to estimate TD, although in some instances this was not possible in our study. De Witt and colleagues (2000) overwhelmingly found the differences in kinematics discovered between running barefoot and when wearing typical training footwear to be present at TD and 30 ms before TD. Given these findings, instances where we predicted TD in kinematic data slightly early, should not be a concern.

In conclusion, runners adjusted running patterns due to wearing footwear with different amounts of underfoot material. In many cases, kinematic parameters were significantly different for both barefoot and very minimal footwear conditions compared to footwear with thicknesses resembling typical training footwear. For some dependent variables, barefoot seemed to separate from all footwear conditions implying that a unique strategies were utilized for barefoot running even when compared to minimal footwear providing very little cushioning or protection. Peak accelerations implied that cushioning limited the shock transferred to the tibia and the head. Most coordination variability measures implied barefoot running to be significantly more variable than running in minimal running footwear. Adaptations due to running in footwear with unknown cushioning characteristics occurred quickly in as few as six to eight steps; however, kinematic adjustments were also occurring later in the six minute runs. Coordination variability implied the most repeatable coordination patterns were not realized until four minutes into the run.

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CHAPTER VI

RESPONSE TO A SUSTAINED RUN IN MINIMAL FOOTWEAR

Introduction

Shoe sales have grown rapidly in the minimal footwear market over the last several years. Minimal footwear, according to the footwear industry, can be defined as a shoe with a thin, flexible midsole and outsole, and a light, basic upper with little or no heel counter. These shoes are typically built with little underfoot material to cushion impacts and protect the foot from environmental factors. A variety of these products are currently on the market. Just a few of the current products include; Vibram's Fivefingers (Vibram USA, Concord, MA), Nike Free (Nike Inc., Beaverton, OR), New Balance Minimus (New Balance Running Shoe, Inc., Boston, MA), and Terra Plana "Vivo' (Terra Plana International, London, United Kingdom).

Squadrone and Gallozzi (2009) used experienced barefoot runners to investigate a minimal or barefoot inspired shoe. Subjects received Vibram Fivefingers (Vibram USA, Concord, MA) and a pair of typical training footwear (TTF) ten days before the data collection to allow them time to become accustomed to these footwear. Subjects ran for six minutes barefoot, with the Vibram Fivefingers, and with TTF. The Vibram Fivefingers resulted in kinematics of the leg and foot which were more similar to barefoot than TTF. For example, the foot was significantly more plantar flexed for the Fivefingers compared to the TTF condition at touchdown (TD). Impact forces were also reduced with the Fivefingers shoe likely as a result of kinematic alterations made to shorten stride length and increase stride frequency. Contact times when barefoot and when wearing the Fivefingers were similar (and less than shod), but flight times were greater for the

Fivefingers. Authors speculate the differences in flight times between the Fivefingers and barefoot runs might be attributed to the little protection the Fivefingers footwear does provide. This protection may help achieve a more vigorous push off compared to barefoot.

Squadrone and Gallozzi did not measure impact shock but the lack of underfoot cushioning when wearing very minimal footwear would suggest the potential for an increase. Light et al (1980) found that when walking, peak tibial accelerations increased two fold when footwear with a thin leather midsole were compared to footwear with shock absorbing midsoles. Therefore it is likely that impact shock has the potential to increase significantly for runners wearing minimal footwear.

For runners accustomed to training in TTF, a minimal shoe would likely provide very different cushioning, protection, and sensations. Runners already accustomed to training barefoot, as the subjects in Squadrone and Gallozzi's (2009) experiment, have likely adopted kinematic patterns sufficient for very little or no underfoot cushioning or protection. Their tissues, including lower extremity musculature and plantar foot surface skin, may have adapted to allow for safe and efficient movement patterns when running barefoot. For these individuals, running in the Fivefingers was probably not an extremely novel task. Conversely, for those who typically wear very protective and cushioned TTF, running in minimal footwear with very little underfoot material is likely more of a novelty. If a very minimal shoe was purchased, a six minute run is likely much shorter than the typical runs wearing the new product. It is likely that a consumer would spend 30 minutes or more on their initial run and subsequent runs, in these footwear.

Several studies have investigated kinematic, loading and acceleration differences from the start to the end of sufficiently long or intense experimental runs. When runners were matched to motion control or cushioned footwear using the arch index, peak tibial internal rotation (TIR) was found to vary over time depending on the footwear type worn. TIR decreased over the course of the run when motion control footwear were worn, and increased when cushioned trainers were worn (Butler, et al., 2007). Eversion variables were also affected by footwear condition as the motion control shoe limited eversion in many low arch runners although statistical significance was not reached. This run was conducted at a self- selected training pace for a 30-45 minute run and was terminated when a "hard physical intensity" was reached. A graded exercise testing protocol was used in another study which found reduced heel loading, increased 1st metatarsal loading, and reduced contact time with fatigue (Willson & Kernozek, 1999). This study included a rapid running pace in combination with an incline angle that increased 2° every two minutes. An exhaustive run was also used to show differences in knee and rearfoot kinematics, tibial accelerations, and impact reductions from start to finish (Derrick, et al., 2002). The knee became more flexed and the ankle joint became more inverted at TD, resulting in greater tibial acceleration and increased shock attenuation compared to the beginning of the run. These runners performed exhaustive runs at a speed simulating their 3200-m time trial at maximum effort. Running patterns are commonly found to change from start to finish over the course of an intense run of sufficient distance.

It is unlikely that someone would perform a run for the first time in minimal footwear at the intensities utilized in the studies above. If this was done, the same running pattern adjustments are likely. If the first run in this footwear is performed at a more cautious pace, the same adjustments are possible and likely dependent on the level of cushioning and protection provided by the footwear. If some of these adjustments are due to cumulative impacts or the perception of harmful loading, less aggressive runs with less protective footwear may show pattern changes (B. M. Nigg, et al., 1987).

The purpose of this study was to investigate how running patterns change in minimal footwear over the course of a thirty minute treadmill run. It was hypothesized that changes in running patterns when wearing minimal footwear would be consistent with findings on barefoot and minimal footwear previously discussed, including a flatter foot placement and more plantar flexion compared to footwear with typical training footwear thicknesses throughout the 30 minute run. Secondly, it was hypothesized that over the course of a 30 minute run while wearing minimal footwear, adaptations would occur throughout the run that would not occur while wearing the other footwear conditions. These adaptations would include a more flexed knee and a flatter foot placement at TD.

Methodology

Subjects

Data from the literature was used to estimate sample size for a minimum statistical power of 80% with an alpha level of 0.05 (De Wit, et al., 2000). Sagittal plane dependant variables utilized in the power analysis included ankle angle, sole angle, leg angle, and the knee angle all at TD. For this reason, ten injury free, recreational male runners between the ages of 18 and 55 who used a rearfoot footfall pattern participated in the study. Subjects performed all runs on a motorized Woodway treadmill (Woodway, Waukesha, WI) at 3.0 m/s for 30 minutes in each of the three footwear conditions following a standard treadmill warm up in their own footwear. For each subject, data collections were done at least one day after the previous collection to ensure sufficient rest from fatigue and impact.

Experimental Set-up

Three pairs of specifically constructed shoes were used in this study. These shoes all utilized a New Balance 790 upper, a lightweight upper with a very minimal heel counter. The midsole of this footwear was composed of cut and buff ethlylene-vinyl acetate (EVA) with an average hardness of 61 Shore 00. Each of the three pairs of shoes had distinctly different EVA thicknesses (Figure 10). One shoe had a typical TTF thickness, one simulated a very minimal, barefoot inspired shoe, and one fell between the previous two midsole dimensions. On the bottom of the footwear, the lateral heel and the medial forefoot had a single basic layer of rubber outsole material attached. Cushioning properties in the rearfoot between footwear conditions were compared using a peak g score obtained with a gravity driven impact tester and were as follows: thin – 40.1 g, medium– 16.8 g, thick – 14.3 g (Exeter Research, Inc., Exeter, NH) (Figure 10).

Figure 10. Footwear conditions utilized in the study. Foam thicknesses (mm) and peak g impact scores are presented.

Running kinematics were obtained at 200 Hz using a Qualisys Oqus motion capture system (Oqus 500, Qualisys AB, Gothenburg, Sweden) and acceleration signals were captured at 1000 Hz using Delsys accelerometers (Delsys Incorporated, Boston, Massachusetts). Retro-reflective markers were attached using two sided tape to the subjects left and right greater trochanter, left medial and lateral femoral condyle, left medial and lateral malleolus, and left 1st metatarsal head and 5th metatarsal head. These markers were used as calibration markers within Visual3D (C-Motion, Inc., Germantown, Maryland). Tracking markers were attached via rigid shells to the heel of the footwear (or the skin on the heel), the leg, and the thigh. One accelerometer was attached rigidly to the inferior, antero-medial leg on the left tibia and another attached rigidly to the anterior aspect of the forehead. The accelerometers were attached securely to the skin using 2-sided tape and were further wrapped with athletic pre-wrap to subject tolerance. Data were collected every five minutes in thirty second increments from the beginning of the run up to 30 minutes.

A key aspect of this study was subjects having modest information about each footwear condition before running. In order to investigate how subjects adjust from their initial steps in a new shoe to well into a sustained run, subjects were not allowed to walk or run in any footwear condition before the test started. To accomplish this, immediately after the test administer put the footwear on the subject, they stood up and boarded the treadmill.

Data Processing

All raw kinematic data were filtered using a dual pass, 2nd order low-pass Butterworth filter with a cut-off frequency of 12 Hz (Hardin, et al., 2004). From kinematic data, local right hand coordinate systems and segment end-points were derived for lower extremity segments. Segment and joint angles were calculated using an Xyz Cardan rotation sequence (Robertson, et al., 2004). For kinematic data, TD was determined using maximum forward position of the heel markers, and knee extension maxima were used to determine touchdown (TO) (Fellin & Davis, 2007). TD was defined to be four frames after these forward maxima through visual inspection. Angles were calculated for the foot, leg, and thigh segments as well as the ankle joint complex (AJC) and the knee.

Raw acceleration data were low pass filtered using the same Butterworth filter with a cut-off frequency of 50 Hz (Boyer & Nigg, 2007). TD and TO were determined in acceleration signals through visual inspection using recurring spikes in tibial acceleration plots. Each stance phase from acceleration signals had means and linear trends removed (Mercer, et al., 2002). Power spectral densities (PSD) were calculated on these sections using a Fourier Transformation. The ratio of PSD for the head to PSD for the tibia was calculated for each frequency within the range of 0-20 Hz. Ratios were averaged across these frequencies to describe shock attenuation. Larger ratios indicated more impact shock attenuation (Derrick, et al., 1998; Mercer, et al., 2002; Shorten & Winslow, 1992).

In order to investigate the effect time had on running patterns, time epochs were created from each five minutes of the treadmill run. The initial time epoch (time epoch 1) included the first 10 steps once the treadmill was up to speed. The remaining time epochs were created using ten steps at the beginning of every five minutes on the treadmill. Therefore, epoch 2 was data from five minutes into the run; epoch 3 was data from ten minutes into the run, and so on.

Repeated measures ANOVA was used to determine statistical differences ($p < .05$) for footwear condition and time. Dependent variables (DV) consisted of three dimensional angles, peak accelerations, and impact attenuation at key instances in time during the support phase. When differences were found between conditions, a Tukey multiple comparison test was employed to locate the locus of the differences.

Results

No significant Footwear Condition × Time interaction was present study wide for any dependant variables. Thus, all time points were averaged when comparing footwear conditions and all footwear conditions were averaged when investigating time related differences.

In general, the amount of underfoot material had an effect on many kinematic variables (Table 7). Sagittal angles at TD including the AJC ($p < 0.001$), knee ($p < 0.038$), foot ($p < 0.001$), and the thigh ($p < 0.001$), resulted in statistically significant differences indicating a more vertical thigh, a more extended knee, and a flatter foot placement with less underfoot material. Additionally, less knee flexion ($p < 0.001$) and stance time ($p < 0.001$) were evident with less cushioned footwear. In the frontal plane, significantly greater eversion was shown when the amount of underfoot material was reduced ($p = 0.007$). Transverse motion of the leg and thigh exhibited similar behavior as more internal rotation was present with more minimal footwear ($p = 0.01$ & $p < 0.001$).

Table 7. Kinematic data values (standard deviation) for each footwear condition as well as probability values from ANOVA averaged across all time epochs. All angles shown are in units of degrees (°) and time in units of seconds (s).

Mean Values (STDEV) for Dependent Variables by Footwear Condition				
	Footwear Condition			
	thin	**medium**	**thick**	**P value**
Kinematic Measures				
Sagittal AJC at TD	8.68[b](3.1)	9.10[b](3.1)	9.99[a](3.1)	<0.001
Sagittal Knee at TD	-9.51[b](5.5)	-10.2[a](5.5)	-10.3[a](5.5)	0.038
Sagittal Foot at TD	18.8[b](4.3)	19.1[b](4.3)	20.4[a](4.3)	<0.001
Frontal AJC at TD	-5.73(2.5)	-5.98(2.5)	-6.14(2.5)	0.38
Sagittal Leg at TD	9.25(4.1)	9.17(4.1)	9.53(4.1)	0.12

Sagittal Thigh at TD	18.7^{b}(3.1)	19.3^{a}(3.1)	19.8^{a}(3.1)	<0.001
Max Knee Flexion	-37.2^{c}(6.4)	-38.0^{b}(6.4)	-39.5^{a}(6.4)	<0.001
Peak AJC Eversion	9.07^{b}(2.6)	9.19^{b}(2.6)	8.44^{a}(2.6)	0.007
Peak TIR	-4.01^{a}(5.2)	-3.52^{ab}(5.2)	-2.82^{b}(5.2)	0.01
Peak Foot Eversion	2.22^{a}(1.7)	1.83^{b}(1.7)	1.50^{b}(1.7)	=0.001
Peak Thigh Int Rot	-4.32^{a}(5.7)	-4.03^{a}(5.7)	-1.44^{b}(5.7)	<0.001
Stance Time	0.267^{b}(0.02)	0.268^{b}(0.02)	0.271^{a}(0.02)	<0.001

Note: Superscript denotes statistically homogenous groups.

Acceleration peaks showed consistent changes as footwear became more minimal (Table 8). Peak acceleration values at the head and leg were greater as underfoot material was reduced ($p < 0.001$ & $p = 0.007$). The transfer function describing impact shock attenuation failed to exhibit statistical differences ($p = 0.22$).

Table 8. Acceleration data mean values (standard deviation) for each footwear condition as well as probability values from ANOVA averaged across all time epochs. Peak acceleration values are in units of gravity (g) while transfer function data are in units of decibels (dB).

Mean Values (STDEV) for Dependent Variables by Footwear Condition				
	Footwear Condition			
	thin	**medium**	**thick**	**P value**
Acceleration Measures				
Peak Head Accel	1.36^{a}(0.31)	1.29^{b}(0.31)	1.25^{b}(0.31)	<0.001
Peak Tibia Accel	6.04^{a}(1.1)	5.85^{ab}(1.1)	5.73^{b}(1.1)	0.007
Transfer Function	-9.19(2.7)	-9.44(2.7)	-9.49(2.7)	0.22

Note: Superscript denotes statistically homogenous groups.

Across time epochs, two DVs showed the initial time epoch to separate from all remaining time epochs and four showed adaptations occurring throughout the run (Figure 11). No acceleration DVs were found to be significantly changing across time epochs. Sagittal TD angle and peak eversion angle of the AJC indicated the initial time epoch on the treadmill to be different than the remaining time epochs ($p = 0.02$ & $p < 0.001$). In the case of peak AJC eversion, the last time epoch narrowly missed being statistically more everted than the second time epoch (0.052). TD position of the sagittal knee and the sagittal thigh indicated changes throughout the run ($p = 0.018$ & $p < 0.001$).

Maximum knee flexion and stance time also exhibited this behavior (p=0.02 & p < 0.001). Figure 11 visually shows all of the dependent variables generally increasing or decreasing as the run progressed. This pattern was also seen in peak tibial internal rotation, peak foot eversion, and peak thigh internal rotation, although significance was not reached for any of these comparisons (p=0.21, p=0.055, p=0.23).

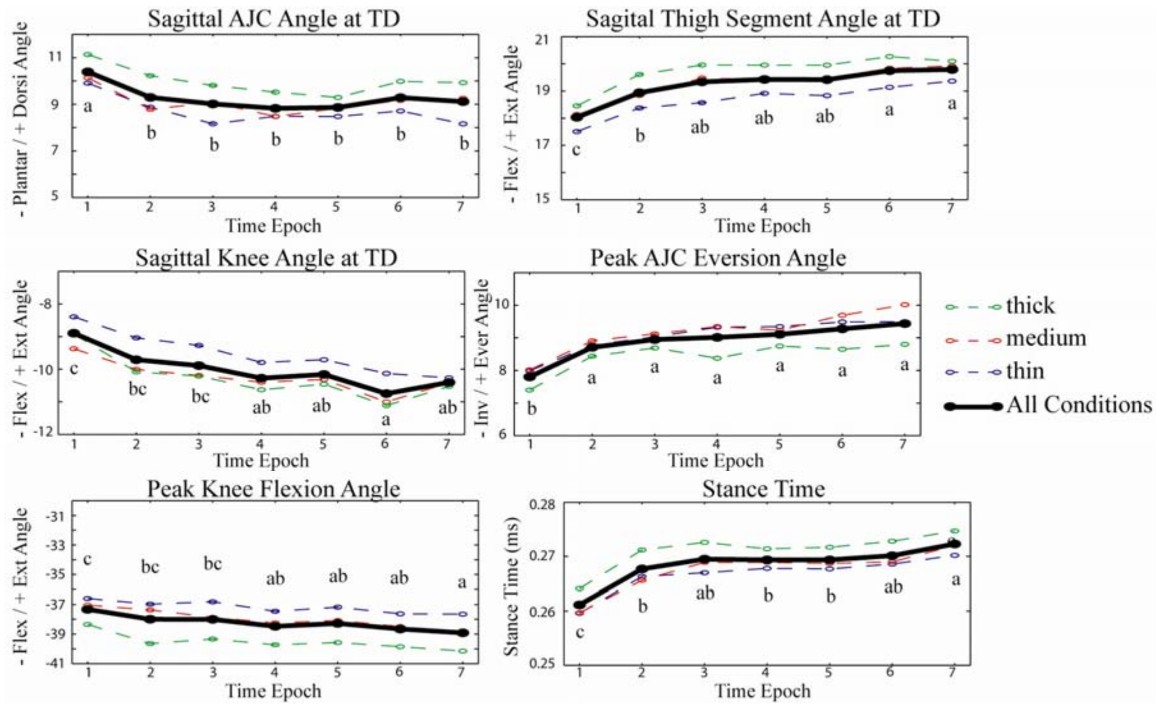

Figure 11. Plots of mean values for significant main effects of time as well as individual footwear condition plots. Statistical differences only apply to mean values averaged across all footwear conditions. Superscript denotes statistically homogenous groups within plot statement used.

Discussion

The purpose of this study was to investigate how running patterns change in minimal footwear over the course of a thirty minute treadmill run. As hypothesized, runners made adjustments to running patterns when wearing minimal footwear which resulted in different running patterns compared to footwear with thicker midsoles. Kinematic variables at the foot, AJC, leg, knee, and thigh showed adjustments resulted from wearing footwear with different amounts of underfoot material. Peak accelerations at the tibia and head increased as underfoot material was reduced.

Runners were found to adjust running patterns as the thirty minute run progressed regardless of footwear condition. It was hypothesized that over the course of a 30 minute run while wearing minimal footwear, adaptations would occur throughout the run that would not occur while wearing thicker footwear such as a more flexed knee and a flatter foot placement at TD. Therefore, this hypothesis was rejected. In general, many kinematic dependent variables showed differences across time epochs. Several dependent variables were found to significantly increase or decrease as the 30 minute run progressed.

Effect of Footwear Condition

Sagittal kinematic adjustments were made as a result of reduced underfoot material and cushioning properties. The sagittal AJC angle at TD exhibited more dorsiflexion for the thick condition compared to the thin and medium conditions as did the foot segment angle. The leg segment was not statistically different across footwear conditions so the majority of this AJC change apparently came from the foot segment. These results generally complied with De Wit et al. (2000) on barefoot versus shod running. Hardin, van den Bogert, and Hamill (2004) found a more extended knee and hip at TD when running on a firmer surface. We found the sagittal knee angle at TD to be more extended for the thin condition compared to the medium and thick conditions. The thigh showed similar behavior to the knee and since the leg showed no change, the thigh likely contributed greatly to knee differences. TD Sagittal plane kinematic adaptations made due to wearing footwear with less underfoot material were consistent with previous works comparing barefoot to typical shod running, firmer surfaces to softer surfaces, and minimal footwear to typical training footwear.

After touchdown, peak knee flexion was greater for the thick condition compared to all others, and the medium condition displayed more flexion than the thin condition. Although Hardin et al (2004), did not find greater flexion for the firm surface condition, De Wit et al (2000) did find more knee flexion at midstance when barefoot was compared to shod. Stance time was greatest with the thick condition compared to all others, as was also found by Divert et al. (2005b) for barefoot versus shod running. Further, Squadrone and Gallozzi (2009) showed increased stride frequency when comparing the Vibram five-fingers to typical training footwear. Our thin condition is likely to produce similar cushioning characteristics to the Vibram shoe used in the Squadron and Gallozzi experiment. Peak knee flexion and stance time proved to relate well to previous research on barefoot and barefoot inspired footwear.

Our results showed footwear with less underfoot material exhibited greater rearfoot eversion relative to footwear with more underfoot material. Cavanagh (1981) stated that footwear with firmer, wider midsoles should be better at controlling eversion/pronation than footwear with softer, narrower midsoles. In the present experiment, each midsole had similar hardness characteristics; however, the midsole widths were different due to the midsole thickness differences. The thin condition had a midsole which was 6.6 cm at the widest part of the rearfoot, the medium shoe was 7.5 cm, and the thick was 8.2 cm. The results for rearfoot eversion and width were consistent with Cavanagh's suggestion. Hamill et al. (1988) found a racing flat showed greater eversion than a training shoe. The racing flat did have a narrower heel base which probably contributed to the increased rearfoot motion. Our eversion differences also relate well to Hamill et al. although their values were generally greater. This discrepancy may be due to the greater intensity and speed utilized by Hamill et al. Clarke et al (1983a) also showed greater rearfoot motion when footwear without heel flares were compared to those with heel flares. The thin footwear in our study had no heel flare; however, the other conditions did. The medium condition had a medium heel flare and the thick condition had a large flare, so our eversion results also agree with Clarke's findings. Consistent with the findings of others, the width and heel flare seemed to be affecting rearfoot motion of these footwear. Although a substantial amount of heel flair is not likely on most modern typical training footwear, the width discrepancy from the thin condition to the thick condition was not unlike the differences between minimal footwear and the typical training footwear available to consumers. Therefore, it is likely when comparing minimal footwear to typical training footwear, greater eversion might be expected possibly due to expected heel width discrepancies.

Tibial internal rotation was greater in the more minimal conditions as might be expected for two reasons. First, eversion and TIR are coupled (DeLeo, et al., 2004; Hicks, 1953). Since a great peak eversion angle was present for the thin condition, a corresponding greater TIR angle was also likely, as was shown. Secondly, Pohl and Buckley (2008) reported relatively greater eversion transferred to TIR when subjects utilized a forefoot landing pattern compared to a heel strike pattern. Although subjects did not in general perform a forefoot strike pattern, given the kinematic results, a less severe heel strike was likely for the minimal conditions. These results would imply more

TIR transferred from eversion for the more minimal footwear which also had greater eversion angles.

Eversion and TIR are often associated with injury (Nawoczenski, Cook, & Saltzman, 1995; Tiberio, 1987; D. S. Williams, McClay, Hamill, & Buchanan, 2001) and our study clearly showed eversion and TIR differences due to footwear. Greater eversion than "normal" may stress biological tissues, and therefore footwear and orthotic interventions are often employed to control this motion (Hamill, et al., 1988). Since eversion is transferred up the kinematic chain into TIR, large amounts of foot eversion may mean excessive tibial internal rotation. This excessive motion could result in non-ideal loading of biological tissues, which could increase propensity for injury. The amount of either motion that is considered excessive is subjective and varies by individual. Minimal footwear do not seem to limit eversion nor tibial internal rotation, and may increase these motions relative to thicker typical training footwear. Those individuals thought to be adverse to increases in these motions should use caution when utilizing minimal footwear.

Opposing the thought that eversion is coupled to TIR and greater eversion causing greater TIR is the notion of proximal to distal energy flow. Bellchamber and van den Bogert (2000) investigated the possibility of TIR being related to what is happening proximally as opposed to what is happening distally. Interestingly, the thigh was more vertical in the sagittal plane and reached greater internal rotation peaks compared to the thick condition. There is a possibility that the footwear conditions were altering running patterns in such a way that the minimal conditions were requiring kinematics related to greater thigh internal rotation. This might be causing the increased TIR, and even the increased eversion. If this was the case, this result could be more related to what the footwear required or allowed of the proximal segments rather than what was required or allowed of the distal segments. Research on proximal to distal versus distal to proximal energy flow has occurred but has been limited; however, these findings may warrant additional research.

Peak accelerations at the head and the leg revealed greater acceleration at both locations as underfoot material is reduced. The results at the leg were consistent with Hardin and Hamill's (2002) research where harder footwear produced greater tibial accelerations. Their peak acceleration values were substantially larger than ours, but they utilized downhill running and a greater running speed which were both likely to produce greater tibial accelerations (Clarke, Cooper, Clark, & Hamill, 1985; Derrick, et al., 1998; Hardin & Hamill, 2002; B. J. Miller, Pate, & Burgess, 1988). When compared to typical training footwear, minimal footwear are likely to produce increased tibial accelerations which may be transferred to the head resulting in greater head accelerations as well.

Effect of Time

Several dependent variables indicated running pattern changed throughout the run (Figure 11). These variables tended to increase or decrease as the run progressed although significant differences were never present between each consecutive time epoch. Some of these kinematic results were likely related. As was seen here, longer stance time was expected to be indicative of greater stride length, which might have been accomplished in part with a less vertical thigh. Verbitsky et al. (1998) found similar increases in stride length. Their study involved running at much higher intensity for 30 minutes. Fatigue and non-fatigue groups were defined post hoc by their end-tidal carbon dioxide pressure. Stride length and peak acceleration increases were only present for the fatigue group. We did not find acceleration increases over the course of the run, but subjects in the current study were not fatigued to the levels of the Verbitsky subjects. Verbitsky's subjects ran at a pace corresponding to their aerobic threshold whereas subjects in our study ran at a speed well below their aerobic threshold.

It is unclear why runners in the Verbitsky et al (1998) and runners in the present study increased stride length during the course of the thirty minute run, but differences in tibial acceleration may be explained due to fatigue. Kinematic pattern adjustments over the course of the run in the present study all favored handling greater loading which the greater stride lengths infer (Clarke, et al., 1985; Hamill, et al., 1995; Hardin & Hamill, 2002). At TD, greater plantar flexion of the AJC and a more flexed knee might both have been employed to deal with greater impact loads (Figure 11). All the footwear conditions utilized were firmer than typical training footwear. A flatter foot placement due to a more plantar flexed AJC was present early for the thin and medium conditions. After five minutes on the treadmill, this occurred across all conditions. Greater knee flexion at TD can reduce the effective mass which has to be decelerated at initial contact, and also would tend to happen when impacts are greater (Denoth, 1986; Derrick, et al., 2002). Related to the effective mass reduction, impact force has been shown to be reduced with greater knee flexion (Gerritsen, van den Bogert, & Nigg, 1995). Greater peak eversion and more knee flexion, which were found towards the end of the run, might have also been utilized to deal with these larger impacts. Hamill et al. (1988) state heel strike impact shock is dampened by a series of actions termed subtalar joint pronation of which eversion is a large proportion. The increased peak eversion may be another attempt to dissipate larger impact forces due to greater stride length. This has been shown in similar studies (Dierks, Davis, & Hamill, 2010). Although the greater midstance knee angle is consistent with increased attenuation of impact, like the other adaptations here, the consequence is increased oxygen cost (Derrick, et al.; Valiant, 1990). All these adaptations seem to be possible in a non fatigued state, but when fatigue becomes too great, the musculature may not be able to control these impacts and larger peak tibial accelerations and even larger peak head accelerations may be expected.

Although no interaction was present between footwear condition and time, these results may have been different had typical training footwear been utilized. All the footwear in this study are considered to have firm midsoles, possibly requiring greater adaptations due to impact than typical training footwear. Although electromyographic data were not considered in this study, some of these adaptations made over time would require greater muscular activation. If minimal footwear require greater adaptations, this increased muscular activation might lead to premature fatigue and the lack of ability to control the impact collision (Dierks, et al., 2010; Radin, 1986). Those unaccustomed to running in very firm or minimal footwear should avoid extreme fatigued states until their tissues have had sufficient adaptation time.

This study had some limitations. Subjects were not allowed practice time in any of the conditions. Consumers are likely to go out and buy minimal inspired footwear then go for a decent run. How they respond for the first time was our research question. We were interested in their initial reactions to these conditions. These results may not translate into how patterns would change after sufficient practice. Finally, utilizing the forward position of the lateral heel counter marker and moving later in time by 20 ms to locate TD likely created a virtual TD in kinematic data which may have occurred prior to the actual TD for some and later for others. This would have affected many kinematic variables at TD. Others have used the vertical position of similar markers to estimate TD with success, although in some instances this was not possible here. De Witt and colleagues (2000) found overwhelmingly the differences in kinematics discovered between running barefoot and when wearing typical training footwear to be present at TD and 30 ms before TD. Given these findings, instances where we predict TD in kinematic data slightly early or late, was not thought to have a great impact on data.

In summary, adjustments were made due to footwear conditions and over the course of the 30 minute run; however changes over time were not dependant on footwear condition. Minimal footwear required many kinematic adjustments in the lower extremities. These adjustments were consistent with previous work on minimal footwear and barefoot running. Generally a flatter foot placement and shorter stance times were found with less underfoot material although tibial and head accelerations were still elevated. Across time epochs, many kinematic measures showed consistent increases or decreases as the run progressed. These alterations were not a result of minimal footwear as all footwear conditions showed these trends.

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CHAPTER VII

SUMMARY AND FUTURE DIRECTION

Introduction

There are some who believe typical training footwear to be overbuilt (Robbins & Waked, 1997a, 1997b; Robbins, et al., 1997) and suggest less underfoot material would be beneficial to runners. Some runners take this to the extreme and run barefoot in an attempt to create a natural running experience unhindered by a shoe upper and unprotected by a shoe midsole and outsole. Minimal footwear has become popular for these runners as well as many simply interested in trying something new. Minimal footwear are often constructed with thin basic uppers and thin, flexible midsoles. It is likely that running in minimal footwear will require adaptation and adjustments as the amount of cushioning and the geometry of the foot/ground interface will be substantially different than what many are accustomed to. This research investigated the effect footwear cushioning amount and the running surface had on running patterns.

Study 1: Cushioning mode and magnitude affect treadmill running patterns

Study 1 utilized two different running footwear conditions and two different cushioned treadmill conditions, as well as a barefoot condition, to investigate the effect cushioning magnitude and mode had on running patterns. The footwear conditions utilized in the study were a production New Balance 1062 (New Balance Athletic Shoe, Inc., Boston, MA) and the other was specifically created for this experiment. This shoe had a very simple upper and midsole with less underfoot material than the New Balance 1062 but more than many minimal shoes. In order to create a cushioned running surface, foam was attached to the treadmill belt. These conditions were similar to the footwear conditions in the amount of material, but the cushioning properties were not identical. Subjects ran at 3.0 m/s for six minutes in each of the five running conditions described while kinematic and acceleration data were collected.

Results of this study suggest that the amount of underfoot cushioning as well as how that cushioning was applied (footwear vs. surface) were both important and affected adjustments made during the run. Kinematic measures as well as peak accelerations indicated adjustments made to running patterns were related to the amount of underfoot cushioning. Kinematic measures indicated barefoot to be different than all others, and acceleration data indicated the most cushioned footwear condition to be different than all others. Kinematic alterations in running patterns also implicated the mode of cushioning to be important. Wearing footwear limited tibial internal rotation and altered sagittal thigh kinematics at TD even though cushioning amount was similar. These results implied wearing footwear affect running patterns which cannot be explained by the cushioning provided. More investigation is necessary to fully understand all the factors involved, but our research showed that cushioning magnitude is not the only factor affecting running patterns when footwear or running surface is altered.

Study 2: Response and acclimation to treadmill running in minimal footwear

Study 2 utilized three footwear conditions as well as a barefoot condition to investigate the effect of running in minimal footwear for the first time. Subjects ran for six minutes at 3.0 m/s for each of the four conditions on an aluminum belt treadmill while kinematic and acceleration data were collected. The three footwear conditions were very similar except for the amount of underfoot material (foam) which varied from very little in the most minimal condition to a typical training footwear amount in the thickest condition. The other condition was in between these two extreme conditions. A key aspect of this study was that subjects had limited information about each footwear condition before the intervention. In order to investigate how subjects adjust from their first step in a new shoe, subjects were not allowed to walk or run in any condition before mounting the moving treadmill. This procedure ensured subjects had as little information as possible before beginning to run. In addition to investigating the differences between running bouts in each footwear condition, the effect of time was also investigated. Particular attention was paid to the changes being realized over the initial 20 steps on the treadmill while also comparing data at each minute of the run.

In many cases, kinematic parameters were significantly different for both barefoot and very minimal footwear conditions compared to footwear which resembled typical training footwear. For some dependent variables, barefoot seemed to separate from all footwear conditions implying that unique strategies were utilized for barefoot running even when compared to minimal footwear providing very little cushioning or protection. Peak accelerations implied that cushioning limited the shock transferred to the tibia and the head. Most coordination variability measures implied barefoot running to be significantly more variable than running in minimal running footwear. Adaptations due to running in footwear with unknown cushioning characteristics occurred quickly in as few as six to eight steps; however, kinematic adjustments were also occurring later in the six minute run. Coordination variability implied the most repeatable coordination patterns were not realized until four minutes into the run.

Study 3: Response to a sustained run in minimal footwear

Study 3 utilized the same three footwear conditions worn in study 2. Subjects ran for 30 minutes at 3.0 m/s wearing each of the three footwear conditions while kinematic and acceleration data were collected. Subjects were required to make three separate visits to the laboratory on unique days for data collections. In addition to footwear condition comparisons, we were interested in the effect of performing a consistent, long run in minimal footwear for the first time. Data were compared across the run using steps from each five minute period throughout the 30 minute run.

Kinematic and acceleration variables indicated adjustments were made to running patterns as a result of changes in underfoot material. Kinematic alterations were made at several joints and segments generally resulting in a flatter foot position and shorter stance times in minimal footwear. These changes did not completely compensate for changes in underfoot material however as peak accelerations at the tibia and the head were increased as underfoot material was reduced. Several kinematic dependent variables were found to be changing as the 30 minute run progressed regardless of footwear condition worn. These alterations over time resulted in a flatter foot placement and a more flexed knee at touchdown as well as longer stance times.

Summary

The amount of cushioning and the mode of cushioning were found to affect running patterns. Given these findings, it is not surprising adaptations were found when comparing running in something minimal footwear to running in footwear with typical training footwear midsole thicknesses. Cushioning magnitude and the geometry of the foot/ground interface were substantially different between the thick, medium, and thin footwear conditions utilized in these experiments. Barefoot running cannot be predicted based on cushioning magnitude or cushioning mode alone. It is apparent that barefoot running may require a unique solution even compared to running in extremely minimal footwear. When runners wore footwear for the first time, some adaptations occurred quickly; however, adjustment were still occurring much later into the six minute and the 30 minute runs. Runners who purchase minimal footwear can expect changes in running patterns as a result of cushioning and geometry differences.

Future direction

We have investigated how runners respond to footwear conditions with little prior knowledge of cushioning characteristics. The focus of these experiments was how and when adjustments were made when footwear with very little cushioning or protection are worn for the first time. Future work should investigate long term changes associated with wearing minimal footwear. It is possible that after sufficient practice with minimal footwear, running patterns may not match running patterns utilized during the first run in this footwear. Therefore, additional research to investigate how running patterns after several months of acclimation compare to the initial run in minimal footwear may be warranted. It would also be useful to study how lower extremity musculature and oxygen cost change over this acclimation time.

The amount of cushioning and the mode of cushioning were found to affect running patterns. Although we did not discover the relative importance of the factors involved in running pattern changes in minimal footwear, it is clear that cushioning magnitude is not the only factor. Additional work is warranted which helps rank which factors are more important for pattern changes when minimal footwear are worn.

Information on which factors are dominating pattern changes would aid footwear companies in developing minimal footwear that truly mimics barefoot running while providing some level of protection to environmental factors.

APPENDIX

INFORMED CONSENT FORMS

Informed consent form: Cushioning mode and magnitude affect treadmill running patterns

Project description

Injuries have plagued runners since the running boom occurred in the late 1970's. Those who suffer from overuse injuries while wearing traditional training footwear may benefit from a change in their kinematic running pattern. This study aims to determine if the cushioning properties of footwear drive how athletes run in shoes. Subjects will run at 3.4 m/s for 6 minutes in each of five conditions (shod and barefoot on aluminum belt treadmill and barefoot on foam covered treadmill). Between treadmill conditions, subjects will rest until their heart rate is below 120 bpm and they report readiness (Hardin, et al., 2004).

Ferris et al. (Ferris, et al., 1999) found that changes to leg stiffness occur rapidly when running on surfaces with different stiffness. In this study, subjects ran over a consistent surface before and after the force platform. The platform was of a different material (and hardness) than was the runway. These subjects completed many practice trials and therefore were prepared to some extent to the surface characteristics of the force platform. This does not seem very applicable to the real world in terms of landing on different surfaces while running.

In order to investigate how subjects adjust from their first step on a new surface, subjects will not be allowed to look at the treadmill belt before they run on it. To get on the treadmill, subjects will place their left foot on the side of the treadmill and use their right foot to gauge treadmill speed before starting to run. The treadmill will be moving at the proper running speed before the subject is on it. This procedure will be used to ensure subjects have as little information as possible before beginning to run.

Kinematic data, transfer functions related to tibial and cranial accelerations, and continuous relative phase were all used in an attempt to ascertain whether cushioning provided through the running surface (foam belt treadmill) and not footwear will result in running patterns similar to barefoot running (aluminum belt treadmill) or typical shod running on a traditional firm surface (aluminum belt treadmill). If running patterns when barefoot on the foam treadmill resemble barefoot running, cushioning is not driving how athletes run in footwear; however if patterns when barefoot on foam resemble shod running, it is possible that cushioning properties of shoes is heavily related to how athletes run when wearing shoes.

Informed Consent Form

Biomechanics Laboratory
Department of Kinesiology
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Amherst, MA 01003

Principle Investigator: Trampas TenBroek, M.S.; Joseph Hamill, Ph.D.

Purpose: To determine if the cushioning properties of footwear drive how athletes run in shoes as opposed to barefoot.

Requirements: You have been asked to participate in this study because you are a male who is a recreational runner with no current injury.

General Testing Procedures: This experiment will take place in one visit to the laboratory. Before data collection begins, you will be asked to complete the following forms: 1) a Physical Activity Readiness Questionnaire and 2) an informed consent form. Height and weight measurements will be taken and reflective markers will be secured to portions of the upper and lower legs. In addition, a lightweight plastic sensor called an accelerometer will be attached to your tibia (shin bone) and your forehead. You will be asked to perform a warm up on the treadmill. You then will perform five 6 minute treadmill runs at 3.4 m/s with running shoes on or barefoot. You will be given adequate rest between these runs and the next will not begin until you are ready. This procedure all should last less than 2 hours. At the end of the procedure, all equipment will be removed from your person and you will be free to go.

Expected Risks or Discomforts: During any type of exercise there are slight health risks. These include the possibility of fatigue and muscle soreness. However, any health risks are small in subjects who have no prior history of cardiovascular, respiratory or musculoskeletal disease or injury. Any ordinary fatigue or muscle soreness is temporary.

Expected Benefits: It is expected that the results of this study will broaden the theoretical basis for understanding running. Knowledge gained in this study can be used to create running footwear which is conscious of the foot's natural motion, potentially leading in a reduction of running related injuries.

Alternative Procedures: There are no alternative procedures that can be used non-invasively to measure these parameters. These procedures are standard for this type of equipment and these measures.

Participant initials_________

Cost and Compensation: The University of Massachusetts does not have a program for compensating subjects for injury or complications related to human subjects research but the study personnel will assist you in getting treatment.

Questions and Answers: Any questions concerning testing procedures, risks, benefits, or participant's rights will be answered by investigators.

Subject Enrollment: It is expected that 10 participants will be enrolled in this study. The study is expected to last approximately 4 weeks but your participation is expected to last approximately 2 hours.

Participation/Withdrawal: You are under no obligation to participate in this project. You are free to withdraw your consent and participation at any time, for any reason.

Confidentiality: All data collected during these sessions will remain confidential with regard to your name and identification. If the data are used for publication in the scientific literature or for teaching purposes, no names will be used and other identifiers such as photographs or videotapes will be used only with your special written permission. You may see the photographs and videotapes before giving this permission.

Additional Information: Should you have any questions about your treatment or any other matter relative to you participation in this project or if you experience a research related injury at any time during this study you may contact Dr. Joseph Hamill via e-mail (jhamill@kin.umass.edu); by telephone (413-545-2245); or by mail (Department of Kinesiology, Totman Building, University of Massachusetts Amherst, 30 Eastman Lane, Amherst, MA 01003). If you would like to discuss your rights as a participant in a research study or with to speak with someone not directly involved with this study, you may contact the Office of Research Affairs at the University of Massachusetts via e-mail (humansubjects@ora.umass.edu); by telephone (413-545-3428); or by mail (Office of Research Affairs, Research Administration Building, University of Massachusetts Amherst, 70 Butterfield Terrace, Amherst, MA 01003).

Participant initials_________

Informed consent form: Response and acclimation to treadmill running in minimal footwear

Project description

Injuries have plagued runners since the running boom occurred in the late 1970's. Those who suffer from overuse injuries while wearing traditional training footwear may benefit from a change in their kinematic running pattern. Minimal footwear may lead to a change resulting in a reduction in their injuries through a shift in the tissues most stressed during running. This study will utilize the aluminum belt treadmill and specially constructed shoes to investigate how athletes will respond to running in footwear considered minimal footwear. The shoes were constructed to be as very basic and as identical as possible in every way except for midsole thickness. Three shoe conditions and one barefoot condition will be used for this study.

Subjects will run at 3.4 mph for six minutes barefoot on the aluminum belt treadmill, and in the conditions. Kinematic data, transfer functions related to tibial and cranial accelerations, and continuous relative phase will all be used to investigate how their running patterns in these footwear compare to barefoot running and running in traditional thickness footwear. Between treadmill conditions, subjects will rest until their heart rate is below 120 bpm and they report readiness (Hardin, et al., 2004).

Ferris et al. (Ferris, et al., 1999) found that changes to leg stiffness occur rapidly when running on surfaces with different stiffness. In this study, subjects ran over a consistent surface before and after the force platform. The platform was of a different material (and hardness) than was the runway. These subjects completed many practice trials and therefore were prepared to some extent to the surface characteristics of the force platform. This does not seem very applicable to the real world in terms of landing on different surfaces while running, or putting on a new pair of running shoes and beginning to run.

In order to investigate how subjects adjust from their first step on a new surface, subjects will not be allowed to look at the treadmill belt before they run on it. To get on the treadmill, subjects will place their left foot on the side of the treadmill and use their right foot to gauge treadmill speed before starting to run. The treadmill will be moving at the proper running speed before the subject is on it. This procedure will be used to ensure subjects have as little information as possible before beginning to run.

Informed Consent Form

Biomechanics Laboratory
Department of Kinesiology
University of Massachusetts
Amherst, MA 01003

Principle Investigator: Trampas TenBroek, M.S.; Joseph Hamill, Ph.D.

Purpose: To gather kinematic, shock attenuation, and coordination information on how runners accustomed to wearing shoes with typical modern midsole thickness (24 mm heel-12 mm forefoot) respond to running in a minimal shoe from their first step until reaching an assumed metabolic steady state after 6 minutes.

Requirements: You have been asked to participate in this study because you are a male who is a recreational runner with no current injury.

General Testing Procedures: This experiment will take place in one visit to the laboratory. Before data collection begins, you will be asked to complete the following forms: 1) a Physical Activity Readiness Questionnaire and 2) an informed consent form. On the first day, height and weight measurements will be taken and reflective markers will be secured to portions of the upper and lower legs. In addition, a lightweight plastic sensor called an accelerometer will be attached to your tibia (shin bone) and your forehead. You will be asked to perform a warm up on the treadmill. You then will perform 4 six-minute treadmill runs at this pace either with running shoes on or barefoot. You will be given adequate rest between these runs and the next will not begin until you are ready. This procedure all should last less than 2 hours. At the end of the procedure, all equipment will be removed from your person and you will be free to go.

Expected Risks or Discomforts: During any type of exercise there are slight health risks. These include the possibility of fatigue and muscle soreness. However, any health risks are small in subjects who have no prior history of cardiovascular, respiratory or musculoskeletal disease or injury. Any ordinary fatigue or muscle soreness is temporary.

Expected Benefits: It is expected that the results of this study will broaden the theoretical basis for understanding running. Knowledge gained in this study can be used to create running footwear which is conscious of the foot's natural motion, potentially leading in a reduction of running related injuries.

Alternative Procedures: There are no alternative procedures that can be used non-invasively to measure these parameters. These procedures are standard for this type of equipment and these measures.

Participant initials__________

Cost and Compensation: The University of Massachusetts does not have a program for compensating subjects for injury or complications related to human subjects research but the study personnel will assist you in getting treatment.

Questions and Answers: Any questions concerning testing procedures, risks, benefits, or participant's rights will be answered by investigators.

Subject Enrollment: It is expected that 10 participants will be enrolled in this study. The study is expected to last approximately 4 weeks but your participation is expected to last approximately 2 hours.

Participation/Withdrawal: You are under no obligation to participate in this project. You are free to withdraw your consent and participation at any time, for any reason.

Confidentiality: All data collected during these sessions will remain confidential with regard to your name and identification. If the data are used for publication in the scientific literature or for teaching purposes, no names will be used and other identifiers such as photographs or videotapes will be used only with your special written permission. You may see the photographs and videotapes before giving this permission.

Additional Information: Should you have any questions about your treatment or any other matter relative to you participation in this project or if you experience a research related injury at any time during this study you may contact Dr. Joseph Hamill via e-mail (jhamill@kin.umass.edu); by telephone (413-545-2245); or by mail (Department of Kinesiology, Totman Building, University of Massachusetts Amherst, 30 Eastman Lane, Amherst, MA 01003). If you would like to discuss your rights as a participant in a research study or with to speak with someone not directly involved with this study, you may contact the Office of Research Affairs at the University of Massachusetts via e-mail (humansubjects@ora.umass.edu); by telephone (413-545-3428); or by mail (Office of Research Affairs, Research Administration Building, University of Massachusetts Amherst, 70 Butterfield Terrace, Amherst, MA 01003).

Participant initials_________

Informed consent form: Response to a sustained run in minimal footwear

Project description

Injuries have plagued runners since the running boom occurred in the late 1970's. Those who suffer from overuse injuries while wearing traditional training footwear may benefit from a change in their kinematic running pattern. Minimal footwear may lead to a change resulting in a reduction in their injuries through a shift in the tissues most stressed during running. This study will utilize the aluminum belt treadmill and specially constructed shoes to investigate how athletes will respond to running in footwear considered minimal footwear. The shoes were constructed to be as very basic and as identical as possible in every way except for midsole thickness. Three shoe conditions will be used for this study.

This study requires three trips into the lab on different days to run in each of the *shoe* conditions described above. Subjects will perform a standard treadmill warm up in their own training footwear prior to beginning each experiment. Subjects will run at 3.4 mph for 30 minutes in a single pair of shoes on each visit. We were interested in the adaptations to multiple, subsequent impacts and not cardiorespiratory fatigue, and thus 30 minutes was chosen to be a sufficient amount of time in each condition (Hardin, et al., 2004).

Kinematic data, transfer functions related to tibial and cranial accelerations, and continuous relative phase were all used to investigate how subjects would run from their first step to beyond metabolic steady state in these minimal footwear and how their running patterns in these footwear compare to running in traditional thickness footwear.

Informed Consent Form

Biomechanics Laboratory
Department of Kinesiology
University of Massachusetts
Amherst, MA 01003

Principle Investigator: Trampas TenBroek, M.S.; Joseph Hamill, Ph.D.

Purpose: To gather kinematic, shock attenuation, and coordination information on how runners accustomed to wearing shoes with typical modern midsole thickness (24 mm heel-12 mm forefoot) respond to running in a minimal shoe for an extended run lasting 30 minutes.

Requirements: You have been asked to participate in this study because you are a male who is a recreational runner with no current injury.

General Testing Procedures: This experiment will take place in three visits to the laboratory. Before data collection begins on the first visit, you will be asked to complete the following forms: 1) a Physical Activity Readiness Questionnaire and 2) an informed consent form. Also on the first day, height and weight measurements will be taken. On each visit, reflective markers will be secured to portions of the upper and lower legs. In addition, a lightweight plastic sensor called an accelerometer will be attached to your tibia (shin bone) and your forehead. You will be asked to perform a warm up on the treadmill before each data collection. You then will perform a 30 minute treadmill run at 3.4 m/s. This procedure all should last about an hour on each visit. At the end of the procedure, all equipment will be removed from your person and you will be free to go.

Expected Risks or Discomforts: During any type of exercise there are slight health risks. These include the possibility of fatigue and muscle soreness. However, any health risks are small in subjects who have no prior history of cardiovascular, respiratory or musculoskeletal disease or injury. Any ordinary fatigue or muscle soreness is temporary.

Expected Benefits: It is expected that the results of this study will broaden the theoretical basis for understanding running. Knowledge gained in this study can be used to create running footwear which is conscious of the foot's natural motion, potentially leading in a reduction of running related injuries.

Alternative Procedures: There are no alternative procedures that can be used non-invasively to measure these parameters. These procedures are standard for this type of equipment and these measures.

Participant initials__________

Cost and Compensation: The University of Massachusetts does not have a program for compensating subjects for injury or complications related to human subject's research but the study personnel will assist you in getting treatment.

Questions and Answers: Any questions concerning testing procedures, risks, benefits, or participant's rights will be answered by investigators.

Subject Enrollment: It is expected that 10 participants will be enrolled in this study. The study is expected to last approximately 8 weeks but your participation is expected to last approximately 1 hour for each visit.

Participation/Withdrawal: You are under no obligation to participate in this project. You are free to withdraw your consent and participation at any time, for any reason.

Confidentiality: All data collected during these sessions will remain confidential with regard to your name and identification. If the data are used for publication in the scientific literature or for teaching purposes, no names will be used and other identifiers such as photographs or videotapes will be used only with your special written permission. You may see the photographs and videotapes before giving this permission.

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Participant initials_________

Statement and Participant Signature (study copy)

The investigators have read and understood the General Guidelines for the Right and Welfare of Human Subjects (Sen. Doc. 79-012) and agree to fulfill these guidelines to the best of their ability

Investigator Signature _______________________________ Date _____________

When signing this form, I am agreeing to voluntarily enter this study. I understand that, by signing this document, I do not waive any of my legal rights. I have read and understood the Informed Consent Document and it was explained to me in a language that I use and understand. I have had the opportunity to ask questions and have received satisfactory answers. A copy of this document has been given to me.

Participant Name ___________________________________

Participant Signature ___________________________________ Date _____________

Address ____

____

Telephone ____

Witness Name ____

Witness Signature _____________________________________

Statement and Participant Signature (participant copy)

The investigators have read and understood the General Guidelines for the Right and Welfare of Human Subjects (Sen. Doc. 79-012) and agree to fulfill these guidelines to the best of their ability

Investigator Signature ______________________________ Date _____________

When signing this form, I am agreeing to voluntarily enter this study. I understand that, by signing this document, I do not waive any of my legal rights. I have read and understood the Informed Consent Document and it was explained to me in a language that I use and understand. I have had the opportunity to ask questions and have received satisfactory answers. A copy of this document has been given to me.

Participant Name __________________________________

Participant Signature __________________________________ Date _____________

Address _______________________________________

____

Telephone _______________________________________

Witness Name _______________________________________

Witness Signature ____________________________________

Modified Physical Activity Readiness Questionnaire

Date ______________________________

Family Name _______________________ Given Name _________________________

Please answer the following questions to the best of your knowledge (circle YES or NO)

YES NO Has a doctor ever said you have a heart condition and recommended only medically supervised activity?

YES NO Do you ever suffer pains in your chest brought on by physical activity

YES NO Have you developed chest pain in the last month?

YES NO Do you ever feel faint or have spells of severe dizziness, passed out, palpitations or rapid heartbeat?

YES NO Has the doctor ever told you that your blood pressure was too high? (systolic $\geq$ 160 mm Hg or diastolic $\geq$ 90 mm Hg on at least 2 separate occasions?)

YES NO Do you smoke cigarettes?

YES NO Do you have a bone or joint that could be aggravated by the proposed physical activity?

YES NO Do you have diabetes?

YES NO Do you have a family history of coronary or other atherosclerotic disease in parents or siblings prior to age 55?

YES NO Has your serum cholesterol ever been elevated?

YES NO Is there any physical reason not mentioned here why you should not follow an activity program even if you wanted to?

Please provide an explanation below for any of the questions to which you answered YES

Questionnaire

Date ______________________________

Family Name ______________________ Given Name ______________________________

Age (in years) ____________________

Gender (circle one) M F

Height ______ feet ______ inches or ____________cm

Weight _______________ lbs or ____________ kg

Please circle one:

Do you use any specialized insoles or foot orthotics? YES NO

Do you have any injuries that may affect the way you walk or run?

YES NO

If YES, please describe the injury, and when it happened:

____

____

____

Did you injure your lower extremity in the last year? YES NO

If YES, please describe the injury and when it happened:

____

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____

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